ASTRONOMICAL PHOTOELECTRIC PHOTOMETRY

A symposium presented on December 31, 1951, at the Philadelphia meeting of the American Association for the Advancement of Science

Edited by

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A Publication of the
AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE
1515 Massachusetts Avenue, N.W., Washington 5, D. C.
1953

Library of Congress Catalog Card Number 53-12745

PREFACE

THE PAPERS collected here were originally presented, in somewhat abbreviated form, at a symposium held in Philadelphia on December 31, 1951 by Section D (Astronomy) of the AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE. The rapid development of astronomical photoelectric photometry has made it manifestly impossible to cover the entire subject in one symposium; hence, the discussion was limited to the problems of instrumentation and techniques.

Recent engineering advances, especially those connected with the development of the multiplier photocell, have brought within the range of telescopes of moderate size problems which could previously be attacked only with large instruments. Nevertheless, astronomers not thoroughly familiar with the field of electronics often encounter serious difficulties in their attempts to design and construct the proper equipment. Frequently, it is even difficult for them to decide what general type of instrumentation will prove most efficient in attacking the particular problems in which they are interested. Even consultation with experts in electronics does not always prove helpful, since such experts are usually unfamiliar with the astronomical aspects of the problems. It is very much hoped that this volume will help such individuals in the design and construction of the type of equipment which will prove most useful to them.

As Dr. Whitford points out in his able summary, we probably do not yet know which of the various techniques finally will prove the most satisfactory. I am inclined to carry this feeling a great deal farther, and to say that the most useful technique may well depend in large part upon the problem involved. On the basis of our present knowledge, I see no reason why the most efficient

technique for the study of variable stars, where the problem is essentially that of making hundreds or even thousands of measures of the relative intensities of two moderately bright stars, should necessarily be the same as the best technique for measuring extremely faint extra-galactic nebulae. Polarization measures may require yet a different approach. In any given case, the "best" method may depend not only on the problem but on the experience of the individual involved and the facilities available to him. We hope that this volume will present a summary which will be useful both to those actively at work in the field and to those astronomers who wish to make photoelectric observations, but who have encountered some difficulty in knowing just how to make a beginning.

In the choice of authors, two general selection rules were applied. First, we felt it desirable to have papers from authors who could themselves be present at the symposium. Secondly, in a symposium comprising only five speakers, we felt it advisable to have no more than one paper presented from any one observatory. While certain of the men who have made outstanding contributions to the field were thus necessarily omitted as authors, the nature of the symposium was such that their contributions were not omitted. This is especially true in the first two papers, where the authors discuss the fields of direct current and alternating current techniques in general, and in the last paper where ultimate limits are considered and a critical summary is given. The third paper is more limited since, so far as we are aware, pulse-counting techniques are being applied to astronomical problems at only one observatory in this country, and the developments abroad are described in another symposium paper.* The fourth paper, describing developments abroad, was presented at the symposium by Dr. Bengt Strömgren. In this volume, however, the papers which Dr. Strömgren summarized at the symposium are presented as written by the authors themselves, except that those by MM. Lallemand and Lenouvel have had to suffer the effects of my translation. In selecting these papers, we again concentrated

* Just before going to press, it was announced that pulse-counting techniques are now in use at Mount Palomar.

solely on new methods and techniques, and neglected the large amount of important photoelectric work being carried on abroad by the more conventional methods discussed in the first two papers.

In conclusion, it may be relevant to point out that the problems of photometry of faint light sources are becoming of increasing importance in certain branches of physics and of engineering. We hope that this contribution may thus be of some interest to scientists in these fields as well as to astronomers.

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THE USE OF DIRECT-CURRENT TECHNIQUES IN PHOTOELECTRIC PHOTOMETRY OF STARS

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AT THE SEATTLE MEETING of the American Astronomical Society in 1940 a symposium was held on "The Photoelectric Cell in Astrophysical Research." [1] Comparing techniques presently used in photoelectric photometry with those prevalent in 1940, two changes stand out in strong relief. One is the increased photocell sensitivity, due largely to the new antimony—cesium photosurface. The other is the great improvements in electronic instrumentation available for measuring and recording photoelectric currents.

The early history of experimental and applied photoelectricity may be found in numerous papers and standard works; most of the latter include extensive references to the original literature.[2-19] An authoritative article by Harold Weaver traces the application of photoelectric methods in astronomical photometry to 1946.[20] In the period prior to the introduction of photomultipliers, many papers described photoelectric installations, observations, and techniques.[21-129]

During these years parallel developments were going on in the field of physics. Numerous articles dealt with photoelectric and related electrical properties of metals, and with the production of sensitive phototubes.[130-192] Other authors concerned themselves with the theory of the photoelectric effect.[193-216] (The references included in these two groups are only representative

of their fields. More extensive bibliographies may be found in the standard works mentioned earlier.)

In the late 1930's P. Gorlich developed a new class of photoelectric surfaces, the most sensitive of which was an "alloy" of antimony and cesium.[217-28] At about this time the technique of amplification by secondary emission underwent a considerable development.[229-35] (See the bibliography by M. Healea,[229] also the article and bibliography by K. G. McKay.[230]) Research projects were initiated at RCA and elsewhere, looking toward the production of high-sensitivity phototubes that would incorporate a secondary electron multiplier in the same envelope with the photosurface. The projects resulted in the development of several new phototubes with very high sensitivities, the 1P21 having the highest quantum efficiency of any in this group. Properties of these tubes may be found in numerous papers.[230-78]

Since their inception, photomultipliers have had extensive application in the general field of radiation measurement.[279-328] The previous list of papers on astronomical photoelectric photometry dealt with the period prior to 1946. In that year Kron published an important article on the application of photomultipliers in astronomical observations. This paper makes a convenient breaking point in the astronomical bibliography. A number of subsequent publications involve use of non-multiplier type phototubes, and references to these appear in the bibliography.[348-437] The listing of general astronomical papers is preceded by a group of papers that discuss the ultimate limits of radiation detectors in general.[329-47] Following the astronomical papers is a separate listing of papers on polarization measurement in astronomy.[438-50] An important consideration in accuracy of measurements is scintillation of starlight.[451-57]

A block diagram for a typical photometric installation appears in Figure 1. One feature which distinguishes the techniques employed with gas-filled phototubes from those utilized with photomultipliers is the much greater value of R required in the former case to realize proper sensitivity. With photomultipliers, the input resistance of the external amplifier rarely exceeds 1000 megohms, whereas with gas-filled phototubes the input resistance

infrequently is less than 10^5 megohms, at least for stellar photometry. In the case of gas-filled phototubes, the single overriding demand on the external circuit is an absence of spurious currents through R. To achieve this goal, it is necessary to use electrometer tubes and resistors isolated from the atmosphere in a sealed and evacuated chamber which also includes the phototube. The most minute attention must be paid to elimination of leakage paths which permit erratic conduction to or from critical points in the circuit. Extensive references in the literature discuss suitable circuits for electrometer tubes. These have been collected with the references to d.-c. amplifiers in the bibliography. Several of the previous references contain important in-

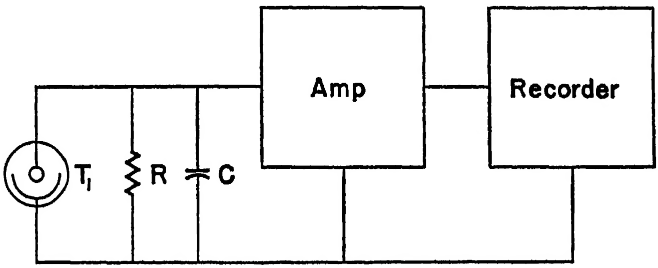

FIGURE 1.

formation regarding electrometer tube circuits, particularly the recent papers by Kron.

The mitigation of exceedingly stringent insulation resistance requirements as one passes from circuits utilizing gas-filled phototubes to ones employing photomultipliers gives greater latitude to the designer for inclusion of additional desirable features in the photometer. The amplifier may be located at some distance from the phototube. It is possible to use other than special electrometer tubes at the amplifier input. Common forms of feedback circuits permit linearization of the amplifier response. This is not to say that crude and careless construction will produce a photometer that performs well. Many of the techniques and precautions for insuring high insulation resistance without introducing deleterious consequences carry over from electrometer tube circuits

to d.-c. amplifiers for use with photomultipliers. To mention only two: (1) Recent measurements have demonstrated that coaxial cables may produce spurious signals that become relatively more serious as the terminating resistance increases.[467] Many present-day photometers use a coaxial cable between the photomultiplier and amplifier. Because of this effect, mounting the amplifier contiguous to the photomultiplier may give improved performance by permitting elimination of a movable connecting cable. (2) Care must be exercised in the use of movable contacts, to avoid generation of extraneous and unwanted signals.[458-70]

The power supply for the multiplier should receive considerable attention, particularly if the design calls for a supply obtained from rectified a.-c. current. There are numerous published discussions of regulators and power supplies.[471-93] The principles involved in low-voltage regulators may be extended to include photomultiplier supplies. Batteries provide a convenient and simple supply and have a very constant emf. Their emf. has a temperature coefficient of about 0.02 per cent per degree centigrade. The chief drawback in the use of a battery supply is the impossibility of voltage adjustment in a convenient manner. A rectifier supply requires great care in its design if the output voltage is to remain sufficiently constant. Both the short-term and long-term stabilities should be better than 0.1 per cent, and preferably should approach 0.01 per cent. One line of attack on this problem under study at Amherst is illustrated in Figure 2. A resistance divider supplies the dynodes of the 1P21. The voltage at a given dynode may be varied by altering the resistors connected to it. Any a.-c. ripple across the output is coupled into the d.-c. amplifier through capacitor C, and so is degenerated out via the d.-c. amplifier and T_1. The long-term stability depends on the a.-c. amplifier and its associated circuits. A wire-wound 10,000-ohm resistor in the resistance divider has a voltage drop across it of 1.018 volts when the circuit is operating properly. The emf. of a thermostated standard cell E_s subtracts from this voltage, so that e should be zero. The electromechanical modulator M_2 converts the error signal e into an a.-c. signal which undergoes amplification by the a.-c. amplifier and synchronous

demodulation by M_1, thereby providing a sensitive control voltage to the d.-c. amplifier. Regarding the voltages on the various dynodes, it is recommended by Dr. G. A. Morton at RCA that the voltage between the cathode and first dynode exceed 90 volts. This is because photoelectrons from the outside edge of the photocathode will not be collected by the first dynode unless it is about 180 volts positive with respect to the photocathode.

Great care must be exercised in the selection of the time constant input capacitor C, Fig. 1. The principal problem involved here is dielectric absorption or "soaking," which causes

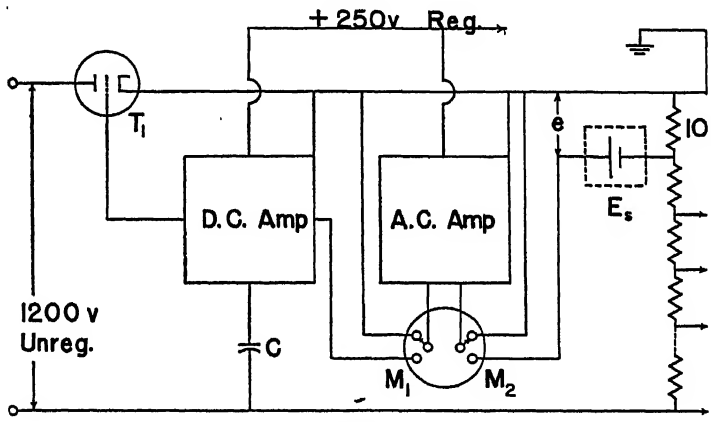

FIGURE 2.

the condenser to depart from ideal characteristics.[408,409] The properties of the input resistor are of equal interest. Most resistors of large resistance value have appreciable thermal coefficients.[403] The current sensitivity of the amplifier and input resistor will therefore change with temperature in the absence of some thermostating scheme. In many cases a slow change in sensitivity is not objectionable, since the observations are differential in nature, and alternate from one object to another at a sufficiently rapid rate to avoid errors arising from thermal transients.

The earliest d.-c. amplifiers for measuring small currents used the FP-54 pliotron. There was considerable difficulty with drift, and the output signal was a nonlinear function of the input.

Later circuits employed balancing techniques which made the output voltage partially independent of the plate supply or filament supply. Negative feedback came into extensive use for improving the linearity of amplifiers.[494-96] The latter designs concerned themselves primarily with instruments for operation from low-impedance sources. It has been only in recent years that linear amplifiers have been designed to operate from source impedances of up to 1000 megohms.

The noise delivered to the amplifier output arises from thermal noise in the input resistor, shot noise from the photocurrent, scintillation effects, and several other sources of less importance. It is of interest to note that the grid current from the first tube may be as large as the dark current from the photomultiplier, and yet the noise contribution from the first is insignificant compared with the second. This arises from the fact that the dark current comes in bunches of electrons, whereas the grid current is a more even flow. On the other hand, it is necessary to give considerable attention to grid current if drift in the output is to be minimized. A refrigerated phototube has small variations in dark current. Variations in grid current may be much larger, depending on the choice of input tube. Minimum ohmic leakage across the tube base is of great importance also. Generally speaking, it is desirable for photometer amplifiers to have input tubes whose grid currents do not exceed 10^{-10} ampere, and values of 10^{-12} ampere are desirable. These figures are based on an assumed sensitivity which produces full-scale deflection on the recording apparatus for a 100-millivolt input signal, and a maximum current sensitivity input resistor of 10^8 ohms. In such a case, a grid current of 10^{-10} ampere will produce a 10 per cent of full-scale deflection in switching the input resistance from zero to 10^8 ohms. A 10 per cent drift in grid current will produce an output drift of 1 per cent of full scale, which is quite noticeable. A grid current of 10^{-12} ampere, for the same sensitivity, produces a deflection of 0.1 per cent of full scale in switching from zero to 10^8 ohms input resistance. This change in itself is inappreciable, and a 10 per cent change in grid current would produce no visible effects on the output.

For photoelectric photometers, the amplifier should be linear to at least 0.1 per cent if one is to avoid tedious references to a calibration chart when reducing observations. A large negative

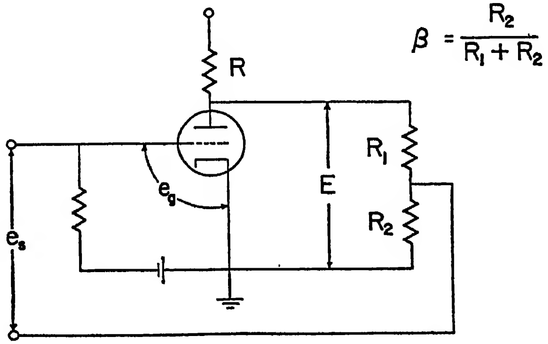

FIGURE 3.

feedback factor will achieve this goal, provided the individual tubes operate in the proper region of their characteristics. Figure 3 illustrates a simple one-tube degenerative amplifier with voltage feedback.

$$E = -g_m e_g \frac{r_p R'}{r_p + R'}$$

$$= -A\,(e_s + \beta E)$$

where

$$R' = \frac{R(R_1 + R_2)}{R + R_1 + R_2}$$

where

$$A = \frac{\mu R'}{r_p + R'}$$

$$\frac{E}{e_s} = \frac{-A}{1 + \beta A}$$

provided $i_p = -g_m e_g$, which assumes g_m is a constant. This condition is not satisfied for large values of e_g, or for a d.-c. grid bias close to cutoff or zero. If the variation in g_m over the range of e_g of interest is small, then

$$i_p = -g_m e_g - \frac{1}{2!\mu^2} \frac{\partial g_m}{\partial E_g} e_1^2$$

where g_m, μ are evaluated at the d.-c. bias point E_g, and $e_1 = \mu e_g \frac{r_p}{r_p + R'}$. If the variation of g_m is larger, it becomes necessary to include higher order terms. Assuming the above relationship, it is easy to show that

$$\left(\beta \frac{E}{e_s} + 1\right)^2 + \frac{1}{Ke_s}\left(\frac{E}{e_s}\frac{1 + \beta A}{A} + 1\right) = 0$$

where β, A have their former meanings, and

$$K = \frac{r_p^2}{2!(r_p + R')^2}\frac{1}{g_m}\frac{\partial g_m}{\partial E_g}.$$

It is worth noting here that differential amplifiers with matched tubes, in addition to their other desirable features, give improved linearity because of high common mode rejection which tends to eliminate even order terms from the output. Generally speaking, a designer has considerable latitude in the choice of operating point so far as variation of g_m goes, whereas the variation of grid current with grid bias changes rapidly and is the determining factor in selecting a suitable operating point.

The most common criticism of d.-c. amplifiers has been that they are subject to drift. This criticism is much less valid today than it was a few years ago, because of the improvements in stabilizing devices. One of the most critical considerations is the regulation of the filament or heater supply. A figure commonly quoted for triodes is that the change in plate current produced by a 10 per cent heater voltage variation equals the change produced by a grid voltage variation of 100 millivolts. If one is using a single-ended amplifier designed for input signals of 0-100 millivolts, then the heater voltage must be regulated to 0.1 per cent to reduce drift, from that source alone, to 1 per cent of full scale. The stringency of this requirement may be diminished considerably by using a differential amplifier as illustrated in Figure 4. If T_1 and T_2 are identical in all respects so that the d.-c. plate currents as well as all derivatives of the plate current characteristics are equal for equal grid voltages, then the output voltage at balance is independent of the heater voltage. Practically speaking, such a situation is never true, even for duotriodes

—and if it were true at one instant it would not remain so because of differential aging effects. If one adjusts circuit parameters so that two tubes have identical plate currents for equal bias voltages, the values of g_m will differ and hence an equal change in operating points will destroy the balance. A measure of the ability of such a circuit to remain in balance for small equal changes of operating point is termed the common mode rejection factor; it is discussed in several of the references concerning d.-c. amplifiers. Rejection factors of 100 are not difficult to achieve; therefore if heater regulation is within 1 per cent in a circuit similar

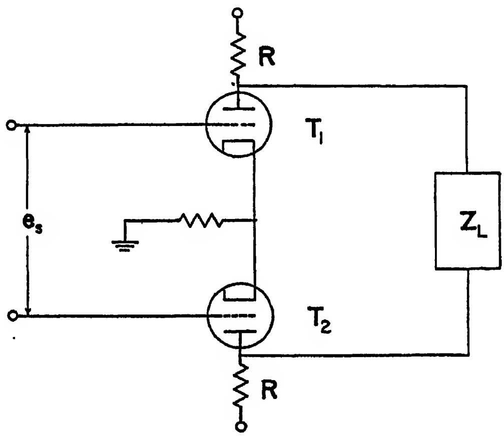

FIGURE 4.

to Figure 4, the output should not have short-term drifts exceeding 0.1 per cent of full scale for the 0- to 100-millivolt input mentioned above. As the tubes age, however, differential effects become accentuated, and the circuit may need rebalancing to preserve a large common mode rejection factor.

Experiments are under way at Amherst using a subminiature amplifier in a circuit similar to those discussed by McFee.[553] In any application involving subminiature tubes with filaments instead of separate heaters and cathodes, the design is complicated by the necessity of having all grids at nearly the same d.-c. potential. The principal advantages are: (1) it is possible to mount the amplifier directly on the telescope, thereby avoiding

microphonics, leakage troubles, and pickup associated with long cables; (2) the power consumed is low, particularly in the filament supply. The latter advantage means that filament supply stabilization becomes simplified. For short runs the entire amplifier may be operated on batteries. Details of the instrument will be published elsewhere.

The characteristics of the indicating or recording device connected to the amplifier output play an important role in the design of the output stage. The Brown Electronik and Leeds and Northrup Speedomax operate most satisfactorily from maximum source impedances of a few hundred ohms. The usual thermocouple applications involve impedances of less than 50 ohms. Larger source impedances affect the damping and induce sluggish operation. In addition, a low impedance connected across the amplifier output (i.e., the recorder) may load the circuit considerably, producing nonlinear operation. These problems must be solved separately in each photometer by adequate study and design.

The reader will find in the bibliography a considerable number of references to d.-c. amplifier design.[497-575] He should consult these for a treatment of the principal problems involved and their solution. The purpose of this paper has not been to give a detailed exposition of the principles involved in the design of a d.-c. photometer, since each installation must meet needs peculiar to its particular application. The references are adequate to illustrate approaches preferred by different investigators in diverse research projects.

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ALTERNATING-CURRENT TECHNIQUES AND SOURCES OF ERROR IN PHOTOELECTRIC PHOTOMETRY OF STARS

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Introduction

THE ADVENT of the photomultiplier and the lead sulfide cell has enabled astronomers for the first time to make efficient use of alternating-current techniques in the photoelectric photometry of stars. The first measurements of this type were made by Y. Öhman in 1942. He has published a detailed description of work carried on at the Stockholm Observatory.[1]

Methods of Detection

Null Methods. Null methods have been successfully used by Öhman[1] and by E. F. Carpenter[2] to measure colors or magnitudes and by Lyot[3] to detect very minute polarization in the sun. The recent work of Walraven is described elsewhere in this series of papers. The important advantage of null methods lies in the fact that requirements placed on the detecting system are relatively simple.

Öhman has made color measurements with a photometer that contains a rotating polarizer. The elements used in this photometer are shown in Figure 1. Use is made of the rotary dispersion of a quartz plate, $Q_{\perp}$, cut perpendicular to its optical

axis to produce a flicker phenomenon with respect to color. The birefringence of quartz plate, $Q_{||}$, cut parallel to its axis, separates the incident energy into two components with their planes of

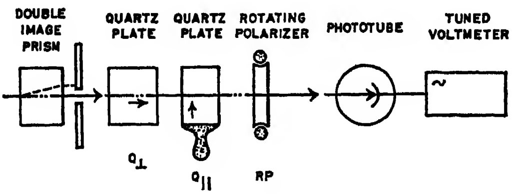

FIGURE 1. Ohman's colorimeter. With this device the influence of the night sky is automatically eliminated.

vibration at right angles to each other. The observer manually rotates this plate until the flicker produced by the rapidly rotating polarizer disappears. The angular position of $Q_{||}$ is then a critical measure of the color of the star. A polarization of the incident light will have no influence on the color.

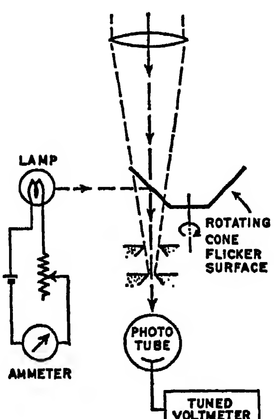

FIGURE 2. Ohman's flicker photometer.

A simple device used successfully by Öhman to measure magnitudes or colors is outlined in Figure 2. The rotating cone consists of six occulting and six transparent sectors. The occulting sectors are painted white on their lower surfaces in order to give

diffuse reflections from a comparison lamp at the side. The solid angle subtended by the diffuse light is made equal to that subtended by the objective of the telescope. Öhman shows that accurate magnitudes can be obtained for stars down to 15.0 photographic magnitude with a 24-inch refractor by simply measuring the lamp current at which the voltmeter shows no deflection. An orange filter was placed in front of the lamp. He suggests two other ways in which the measurements can be made after a balance is achieved: (1) a second phototube could be used to measure the major part of the light from the lamp and (2) the position of an optical wedge required for balance

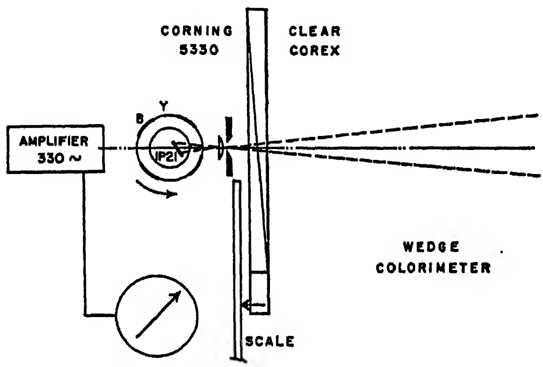

FIGURE 3. Carpenter's wedge colorimeter.

could be determined. He found that two observers were required to run his photometer, one to adjust the lamp and watch the voltmeter and the other to read the ammeter. Each of these functions could of course be performed automatically with more instrumentation.

A sketch of Carpenter's wedge colorimeter is shown in Figure 3. Alternating blue and yellow filters are mounted on a rotating lucite cylinder surrounding the photomultiplier. In front of this color chopper is a color wedge which is used to change the brightness of the yellow light of a star until the output of the tuned amplifier is zero. This wedge is made of glass, and its calibration is permanent. Carpenter has obtained satisfactory results with this efficient colorimeter.

Linear Methods. Another important class of amplifiers are used in which the rectified output current is the measure of light intensity. In an ideal a.-c. amplifier, its d.-c. output should be strictly linear with the alternating current applied at its input. Diodes and triodes when used alone as rectifiers are essentially nonlinear devices; curvature in their characteristic curves is always apparent at low input voltages. There are at least two methods of making the outputs of diodes and triodes appear more nearly linear. In one of these the a.-c. voltage is built up to large values before it is rectified. In the second method, such as that designed by W. Wilson[4] for the amplifier used by G. P. Kuiper

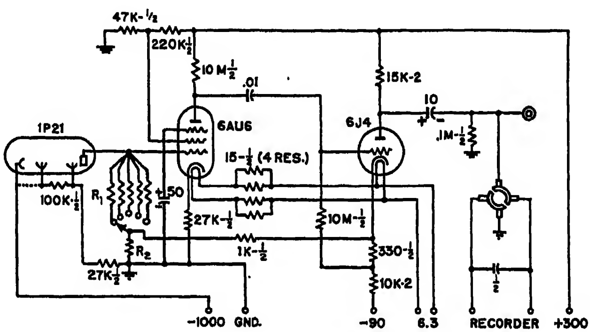

FIGURE 4. Circuit diagram of synchronous amplifier of Marlowe and Pemberton.

at McDonald, negative current feedback makes the output more nearly linear.

An a.-c. amplifier with synchronous detection can be made as nearly linear as desired and no loss in linearity is incurred by the rectifying process. This type requires a synchronizing mechanism in addition to the scanning system, a requirement which can be an advantage because the amplifier will rectify only that current which is admitted at a prearranged phase.

A simple form of synchronous amplifier which has come to our attention is that built by Marlow and Pemberton[5] for the study of the night sky. The rectification is performed in the output circuit of the amplifier by means of a commutator mechani-

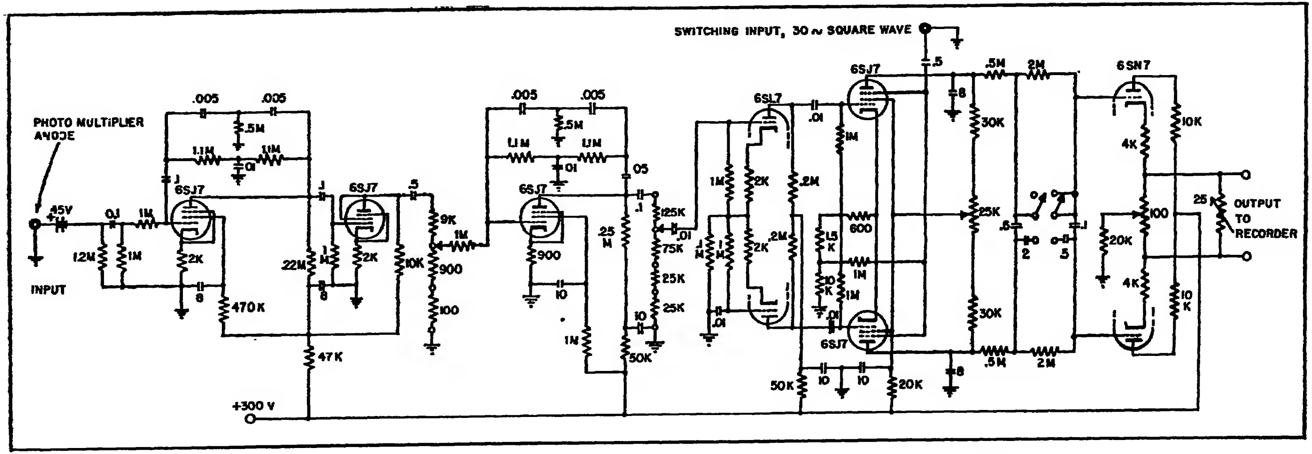

FIGURE 5. Synchronous amplifier in use at the Naval Observatory. The above circuit has recently been modified to provide full-wave rectification. An expected gain of $\sqrt{2}$ in signal-to-noise ratio has not yet been achieved.

cally linked to the scanning mechanism. The circuit is shown in Figure 4.

A more elaborate form of synchronous amplifier has been used for polarization measurements[6] at the Naval Observatory. In this case a synchronizing voltage is generated by means of a commutator geared mechanically to a rotating analyzer. The circuit diagram of the amplifier is shown in Figure 5 and a block

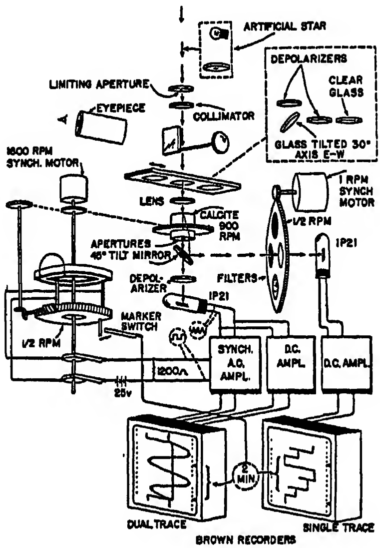

FIGURE 6. Multipurpose photometer capable of measuring polarization, magnitude, and color simultaneously. The large range of input voltage with linear response, gain adjustment beyond the initial stage and an output near ground potential make the Kron d.-c. amplifier (*Ap. J.* 115, 7, 1952) very well suited for use in parallel with the a.-c. amplifier.

diagram of the equipment is presented in Figure 6. The phase of the synchronizing voltage with respect to that of the incoming signal is automatically changed in a two-minute period by means of a separate gear train tied to the same synchronous motor. As a result the light from a star showing polarization causes a sine wave to be drawn every two minutes on an automatic recorder. The amplitude and phase of this sine wave is a measure of the degree and plane of polarization.

A. A. Hoag has designed and used an a.-c. photometer with synchronous amplification at the Naval Observatory in which an occulting sector driven by a synchronous motor is used to chop a collimated beam of starlight. A permanent magnet generator, driven by a second synchronous motor, not attached to the telescope, is used to provide the phasing voltage. For practical purposes a contant phase difference is maintained between the two motors. Satisfactory measurements[7] of the colors and magnitudes of stars down to magnitude 14 have been obtained with the 40-inch telescope.

A. E. Whitford used an auxiliary photocell, light source and chopper to produce a synchronizing voltage for the a.-c. amplifier used in his infrared survey[8] of the Sagittarius region.

The polarimeter designed by Lyot[3] and discussed in detail later contains an a.-c. amplifier with a rectified output similar in principle to that shown in Figure 4. The angular displacement of a fluxmeter was, for practical purposes, found to be proportional to the degree of polarized light for a predetermined time of measurement.

Performance Limitations at Washington, D. C.

A survey has been made at the Naval Observatory of the various factors which limit the accuracy of photoelectric photometry. Many of these limitations are common to astronomers doing photoelectric work in or near large cities. Also, the results obtained here in some cases apply equally well to the performance of photometers in operation at much more favorable sites. For these reasons the results of this survey may have general interest.

A simple circuit for a noise meter, kindly suggested to us by R. C. Jones of the Polaroid Corporation, was used in making the noise measurements. A detailed description of this equipment and its calibration will be published later in connection with measurements of scintillation. As used for the few tests made in connection with this discussion its half-power points were at

0.2 and at 4 cycles per second. A modified General Radio 715-A amplifier was used for the necessary d.-c. measurements.

Basic Data Chart. At a previous symposium Kron[9] introduced a performance chart which permitted one to determine at a glance the factors which limit overall performance for a given photometric installation. With the advent of the photomultiplier, noise produced in the input circuit of the amplifier could be made unimportant; Kron[10] first demonstrated this and Harold L. Johnson[11] has more recently discussed it in considerable detail. This simplification, together with extensive quantitative measures of scintillation, now permits us to separate the sources of error with greater accuracy.

The data on which our performance chart rests were obtained from d.-c. and noise observations made at the 40-inch telescope. Before striking the photomultiplier the light was reflected from two aluminized mirrors and traversed four uncoated lenses. When near the zenith an AO star of magnitude 6.0 was found to produce 7×10^5 photoelectrons per second or a primary current of 1.1×10^{-13} ampere. This observation fixed the single point necessary to establish the line marked "Signal" in Figure 7.

The magnitude at which noise caused by scintillation equals that produced by shot effect only is a very convenient figure used to good advantage by Johnson in his discussion of the ultimate limits of astronomical photoelectric photometers. With a 4-inch telescope Mikesell has found that this magnitude for early type stars was 6.1, 5.8, and 7.3 respectively on three different nights. His measurements were made at 30 cycles per second and a bandwidth of 6 cycles per second. Since the signal increases with the square of the aperture, its shot noise increases directly with aperture. The scintillation noise for a given telescope and seeing conditions is proportional to the signal. When the aperture is increased, however, the increase in scintillation noise is much less than the increase in signal caused by the change in aperture alone. Scintillation measurements[12] were made at 45 cycles per second, on 18 nights with 4- and 8-inch apertures. When the aperture was doubled the average increase in scintilla-

tion noise was 100 per cent; this means that the scintillation noise, like the shot noise, increased directly as the aperture.

I have used the noise meter mentioned above in conjunction with the 40-inch telescope to find the magnitude at which the scintillation noise equaled the shot noise. On a night of average

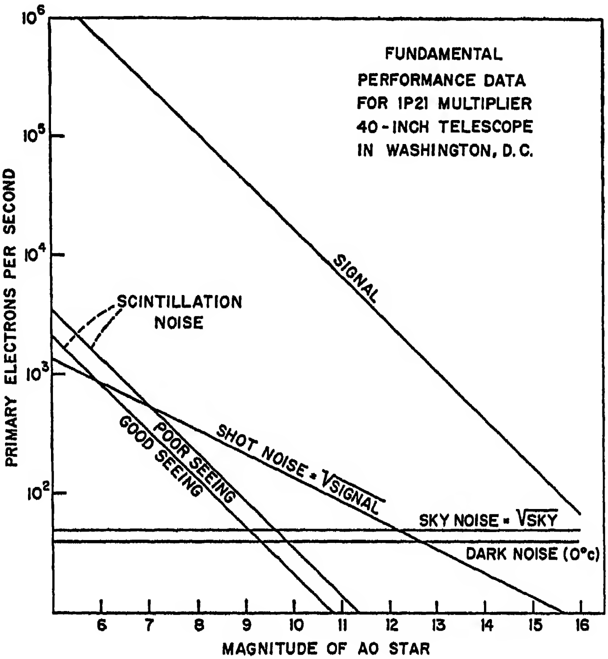

FIGURE 7. Performance data used to compute the errors shown in Figure 8. The scintillation noise is typical of that found within the frequency range 0–50 cycles per second.

seeing it was at magnitude 6.5 and on a night of very bad seeing it occurred at magnitude 7.1. Although these measurements were made primarily within the range 0.2 to 4 cps., other observations together with scintillation spectra obtained here indicate that a similar crossover point would be found for any region short of about 50 cycles per second.

The "Signal" line in Figure 7 has been explained above. The

remaining lines represent root-mean-square deviations produced after one second by known causes. Each line was established as follows:

(1) The shot-noise line indicates the root-mean-square deviation of the signal or the square root of the number of electrons per second.

(2) The scintillation-noise lines are made to intersect the shot-noise line at magnitudes 6.0 and 7.0 and to lie parallel to the signal line because the scintillation noise for a given aperture is proportional to the signal.

(3) The direct current caused by a sky background of 700 square seconds of arc was expressed in electrons per second. The sky-noise line denotes the square root of this number.

(4) Since most of the dark current is not due to cathode emission, the dark noise could not be determined in the same way as was the sky noise. From routine measures with a high-gain a.-c. amplifier the dark noise from the photomultiplier at a temperature near 0°C. was found to be 80 per cent of the sky noise at 30 cycles per second.

We will now transform the data shown in Figure 7 to errors of measurement. These errors depend on the time constant we choose for our amplifying system and on the portion of the frequency spectrum used. The reason for the importance of this second condition is the change in scintillation with frequency. If we use the notation of Johnson and consider the case in which a single resistance (R) and capacity (C) limit the bandwidth of a d.-c. amplifier then if

q = the charge on the electron = 1.6×10^{-19} coulomb
I_1 = the initial photocurrent from cathode in amperes
M = the multiplier gain
f_0 = the half-power bandwidth = $1/2\pi RC$

the mean-square-noise voltage across the input resistor is

$$\overline{E^2} = \pi q I_1 M^2 R^2 f_0$$

In the case of an a.-c. amplifier with bandwidth Δf,

$$\overline{E^2} = 2q\Delta f I_1 M^2 R^2$$

For an a.-c. amplifier the overall time constant may be determined almost entirely by an RC circuit in its d.-c. output. Let us therefore limit this discussion to a d.-c. system with a time constant of two seconds which corresponds to an f_0 of 0.080 cycle per second. For practical purposes a reading may be taken after a 10-second interval. The signal-to-noise ratio, S/N, is given by

$$\frac{S}{N} = \frac{MRI_1}{(\pi q f_0 I_1 M^2 R^2)^{1/2}} = 5 \times 10^9 (I_1)^{1/2}$$

The probable error of one measurement due to the fluctuations in I_1 is given by

$$\text{Probable error} = 0.6745 \frac{N}{S} = 1.3 \times 10^{-10} (I_1)^{-1/2} \qquad (1)$$

The above well-known formulas are to be regarded as approximations; no account has been taken of the shot noise from the first and second dynodes or of possible statistical fluctuations in the secondary emission.

We will consider three cases in which the value of f_0 is assumed to be 0.080 cycle per second: (1) a d.-c. photometer, (2) an a.-c. photometer with a light chopper, (3) case (2) above with a color filter which transmits one-third of the light.

To evaluate the errors for case (1), the fluctuations of the signal current (shown in Figure 7) were converted to probable errors due to shot noise only for a number of magnitudes by means of relation (1). The relative sizes of all the errors under discussion can be found from the data presented in Figure 7, and, since the probable error due only to shot noise has been computed, all the resultant errors may be found immediately.

The probable errors computed in this way for a d.-c. photometer with a two-second time constant are shown in Figure 8(a). The contribution of each factor to the resultant error at each magnitude may be readily seen.

In order to predict the probable errors for case (2), that of an a.-c. amplifier and light chopper, the same procedure was used after the data in Figure 7 had been modified in the following way. The value for the signal current was halved, the values for the shot, scintillation, and sky noise were divided by $\sqrt{2}$, and the

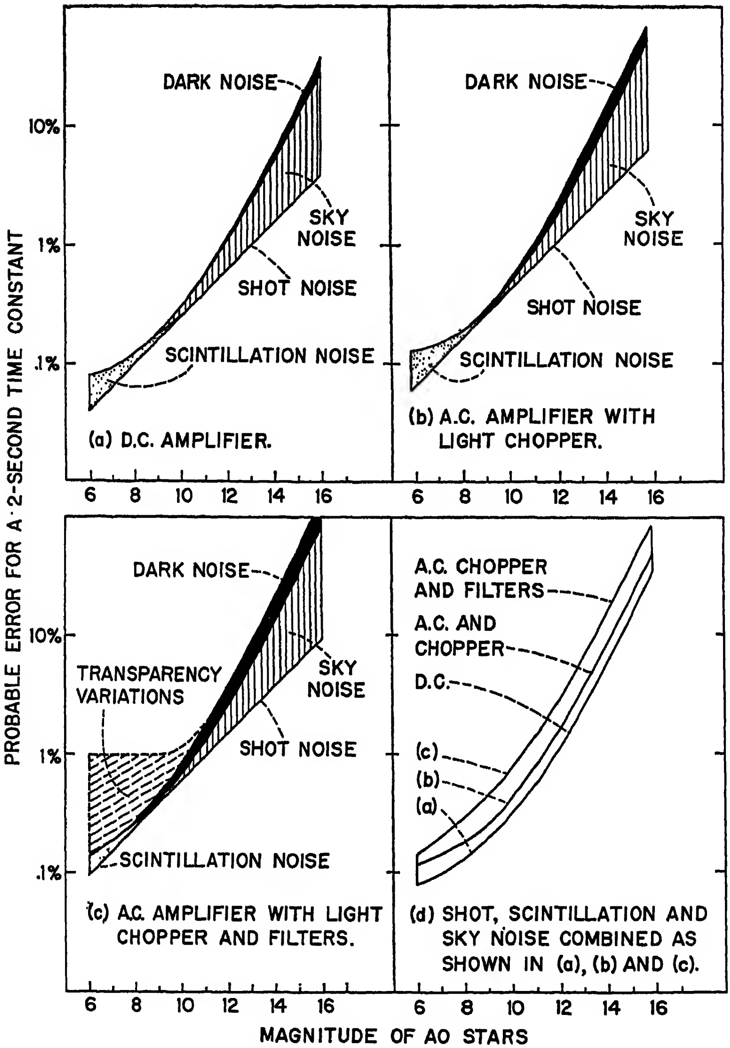

FIGURE 8. Probable errors of one observation computed from the data shown in Figure 7 for average seeing conditions and for different types of photometers, each having a time constant of two seconds. The loss of accuracy caused by any one source of error (shaded areas) depends in some cases on the order in which the errors are combined. For the above presentation the resultant errors were computed in the usual manner by successively combining the inevitable errors due to shot noise with those caused by scintillation, sky brightness, and dark emission.

dark noise was left unchanged. The errors predicted for this pattern are indicated in Figure 8(b).

For case (3), an a.-c. amplifier with chopper and a filter which transmits one-third of the light, the value for the signal current shown in Figure 7 was divided by six. The scintillation noise was divided by the factor $3\sqrt{2}$. The shot noise and sky noise were divided by $\sqrt{6}$, and the dark noise was left unchanged. The predicted errors are shown in Figure 8(c).

In Figure 8(d) the three lines represent the resultant errors for the three cases described above but with zero dark noise.

Before we compare the observed with the predicted accuracy it is instructive to separate photoelectric photometry into two categories, star-to-star photometry and single-star photometry. By star-to-star photometry we mean the comparison of brightness of one star with another when their angular separation is so great that separate settings of the telescope must be made. Single-star photometry, such as colorimetry, spectrophotometry and polarimetry is that form where different characteristics of the light from one star are being studied, even though measures of a number of stars may be necessary on any particular night in order to establish useful results. Not included in this classification is Walraven's technique in which rapid comparisons are made between two stars with small angular separation.

Star-to-Star Photometry. Actually no such accuracy as is indicated in Figure 8(c) has been achieved at the 40-inch telescope at the Naval Observatory. Our experience has shown that the probable error of one measure of magnitude with a color filter and a.-c. amplifier is about 0.010 magnitude for all stars brighter than tenth magnitude. For stars fainter than the eleventh magnitude the predicted errors agree with experience. The dashed line in Figure 8(c) represents the accuracy that has been obtained here under favorable weather conditions.

When star-to-star photometry only is considered it is apparent that:

(1) Scintillation places no practical limitation on accuracy. An exception to this is the case where stars of very large zenith distance are compared.

(2) Sky illumination in Washington begins to decrease the accuracy at magnitude 10 and is a very serious limitation at magnitude 14.

(3) The multiplier should be cooled for measurements of stars fainter than about the tenth magnitude. This is of particular importance during hot weather.

(4) Variable transparency undoubtedly seriously limits the accuracy obtained for bright stars. (These variations evidently permit observers with small telescopes to achieve accuracy which for bright stars may equal or even exceed that obtained with large telescopes for the same stars.) The location of the telescope and the quality of the night are of prime importance.

Single-Star Photometry. Although the prospect of accurate photometry in Washington is not good when two stars are compared, it is possible to achieve an accuracy compatible with the size of the telescope and the brightness of the sky above it when observations of the same star are made simultaneously either in different spectral regions or in different planes of polarization. The long-period changes in transparency can in such cases be removed from the observations. This can be done most readily in polarimetry because atmospheric absorption is the same in all planes of polarization. Since this absorption is not the same in different spectral regions, changes in absorption can cause second order errors in colorimetry and spectrophotometry.

The polarimeter[18] outlined in Figure 6 has been used to measure simultaneously the polarization and color of stars. Since the a.-c. amplifier sees only the *polarized* component of the starlight, small changes in transparency would enter the output of the amplifier directly only if the starlight were completely polarized. If the starlight were polarized 1 per cent and a change of 5 per cent in light intensity occurred, the change in the observed polarization would be 0.05 per cent. The accuracy of measurement of the degree of polarization for such a polarimeter, where transparency variations only are considered, is therefore greatest near its limit of detectability. Observed probable errors of the degree of polarization increase from 0.15 per cent for stars of the sixth and seventh magnitude to 0.4 per cent at the tenth magnitude.

After allowance is made for the time factors involved in securing these observations, the agreement between observed and predicted values is satisfactory. The errors shown in Figure 8(b) most nearly apply to this special case.

In its initial form, this polarimeter gave no sure indication when slow changes in transparency occurred. More recently the d.-c. current from that multiplier used for measuring polarization has been used to monitor the transparency and a record of the sky conditions has been displayed on the same sheet as the polarization measurements. It is expected that this produces an improvement in accuracy because changes which occur during the two minutes required for a complete observation can be recorded and, if desired, used to correct the observations.

A polarimeter containing two 1P21's in which a calcite block was used to separate the polarized components has been tested here. The light passed through a rapidly rotating disk consisting of halves of equal thickness, one half was clear glass and the other a depolarizer. The light next traversed the calcite, and each of the two beams struck separate multipliers. Polarized starlight produced a 30-cycle signal. Any 60-cycle-per-second flicker caused by the boundary of the rotating half disks was rejected by the amplifier. The difference in the a.-c. voltages of the two multipliers was amplified, rectified, and appeared as a sine wave on a Brown recorder as the calcite block and the two multipliers were uniformly rotated through 180°. The seeing noise produced by bright stars was 75 per cent balanced out. We have not yet been able to obtain, however, greater accuracy than that found for the polarimeter described in Figure 6.

Single-Star Photometry Elsewhere

Lyot[3] has constructed a polarimeter which has very high accuracy. A block diagram, which corresponds to his description, is shown in Figure 9. The rotating member consists of two half-disks of cellophane (half-wave "plates") so arranged that it rotates the plane of polarization of the incident light at one time

45° to the right, at another 45° to the left. It carries also a commutator which is used to rectify the output of the amplifier to direct current. A fixed double-image prism separates the light into two completely polarized components which strike separate photomultipliers. These produce two signals 180° out of phase if the initial light is polarized. These signals are added in the amplifier,

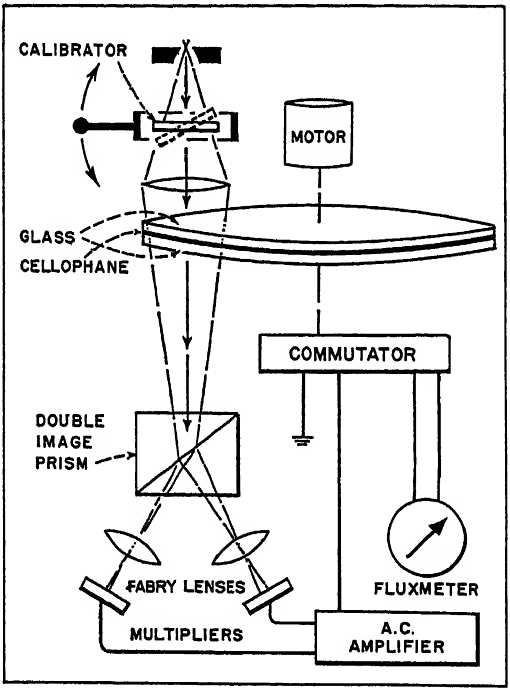

FIGURE 9. Lyot's polarimeter.

rectified, and indicated by the deflection of a fluxmeter. The degree of polarization is found with the aid of a glass plate, which can be rotated about an axis at right angles to the optic axis. Such measures are made with the entire equipment placed at two different position angles.

Lyot shows that the accuracy of a dual system in which two multipliers are used is greater than that in which one multiplier alone is used by a factor of $\sqrt{2}$. He states that this equipment is

insensitive to variation in the intensity of the unpolarized light and to other minor disturbances.

W. A. Hiltner has reported[14] extremely high accuracy obtained on bright stars with a polarimeter attached to the 82-inch telescope consisting of a Wollaston prism and two EMI 5311 multiplier phototubes. The d.-c. difference in output of the two multipliers is amplified and recorded as the equipment is rotated

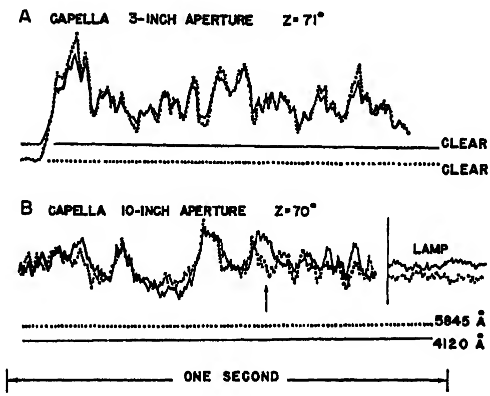

FIGURE 10. Color Scintillation. The starlight is divided and made to strike two photomultipliers; the signal from each controls one trace of a dual-trace oscillograph. The base lines may be used to estimate the gain of each photometer. In A no color filter was placed in front of either cathode; in B two interference filters with the indicated wavelengths of maximum transmission were used. A strong correlation in both phase and amplitude is apparent even when these wavelengths differed by 1725 A.

about the optical axis. He found that the ill effects of seeing noise can be substantially reduced by this arrangement when bright stars are observed with the 82-inch telescope.

It has been stated above that transparency changes enter as second-order effects in spectrophotometry whenever measurements are made simultaneously in a number of spectral regions or whenever colors are measured by rapid-scanning devices such as those already described. The more nearly the signals caused by each color are equalized the smaller the errors due

to variable transparency; the accuracy should be intermediate between that found in polarimetry and that obtained in colorimetry in which observations of many seconds each are made with a sequence of color filters.

Hiltner and Code[15] have tried an interesting device for reducing the scintillation noise in which about 10 per cent of the starlight entering the slit of the spectrometer is made to strike a second photomultiplier. Circuits are so arranged that rapid changes in intensity caused by scintillation were almost completely removed from the output. Hoag[12] has obtained some quantitative data which show that the useful range for such measurements is considerable. Figure 10 gives further examples of the extent of this coherence in those spectral regions where the 1P21 is most sensitive.

Performance Factors and A.-C. Techniques

Shot Noise. This is an ever present and seemingly unalterable limitation on accuracy. Kron[10], Whiteford[16], and Engstrom[17] have found that the shot noise in the output of a photomultiplier agrees reasonably well with that predicted by theoretical considerations. Since the shot noise from photomultipliers has been found by several observers to be the same per unit bandwidth over an extensive frequency spectrum, there is no possibility of selecting a pass band in which the shot noise has a minimum value. Amplifiers having a.-c. characteristics are therefore of no particular advantage in this regard.

The performance of five yellow-based 1P21's was measured at the Naval Observatory with the noise meter and d.-c. amplifier mentioned above. Although the characteristics of each of these five multipliers were widely different, after the differences in gain and dark noise were taken into account, the same cathode photocurrents were found to produce the same shot noise. Of particular interest was the case of a multiplier having exceptionally large dark noise.

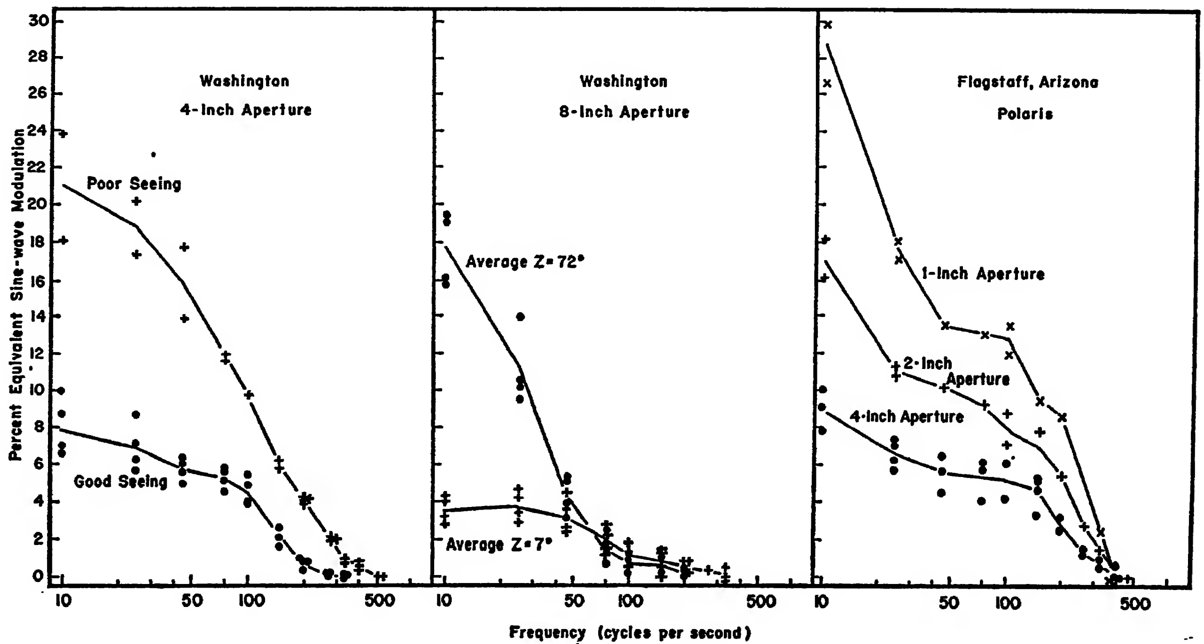

FIGURE 11. Typical scintillation spectra. Cases showing the least and greatest scintillation observed in Washington over a two-year period were in each instance exceeded by scintillation spectra obtained during a two-week stay at Flagstaff, Arizona. In each case the central frequency of a 6-cycle-per-second band is plotted as the abscissa.

As the efficiency of the photosensitive surface increases the shot noise becomes relatively less important. If this efficiency is doubled the ratio of shot noise to sensitivity is decreased by the square root of two.

The quantum efficiency of run-of-the-mill RCA multipliers at a specified wavelength may be found from published handbook data. That of the 1P21 is 11 per cent at 4000 A. The recently developed RCA 6199 multipliers (head-on-type) have the same typical values for quantum efficiency at 4000 A. An interesting paper showing the distribution in cathode sensitivity of a number of RCA type 5819 tubes has been published by Engstrom[18], Stoudenheimer, and Glover. The maximum possible efficiency would correspond to a quantum yield of 50 per cent if half of the electrons released do not escape. At the 1952 Rome meeting of the I.A.U., A. Lallemand of the Paris Observatory reported cathode efficiencies of 25 per cent for surfaces used in his electronic receiver.

Scintillation. Although scintillation does not seriously affect star-to-star photometry, it is desirable in some cases to minimize its effect in spectrophotometry or polarimetry.

Quantitative measures of scintillation have been in progress at the Naval Observatory during the past three years. Other recent observations have been secured by Ellison and Seddon[19] and by Butler.[20] The distribution of scintillation with frequency found by Mikesell, Hoag, and Hall [12] is reproduced here for several different conditions in Figure 11. More recently, Mikesell has extended the frequency range of investigation down to 0.1 cycle per second. His preliminary results (unpublished) show nearly constant fluctuations within the frequency interval from 10 cycles per second to 0.1 cycle per second. These measures at 0.1 cycle per second are close to the region where d.-c. amplifiers operate.

It is not yet clear what part of the fluctuations at this low frequency is due to scintillation and what part is caused by variable transparency. The fact that similar seeing patterns have been observed above 10 cycles per second at Washington and at Flagstaff, Arizona, would indicate that fluctuations in this region are not rapid transparency changes of local origin. Further evidence

of this has been found in the case of observations, made on one night in Washington, of a very small light source (less than 3 millimeters in length) carried aloft by a helicopter. At 8000 feet the scintillation of this light at 30 cycles per second was less than 10 per cent of that caused by Arcturus near the meridian and at the same angular altitude. A westerly wind of 16 knots at 5000 feet present at the time would lead one to suspect that the dust and smoke from the city in the line of sight were well below 8000 feet. Further observations of this nature made at very low frequencies should enable us to separate these factors to a limited extent.

It is evident from Figure 11 that if one wishes to reduce the effects of scintillation in single-star photometry without seeing compensation, an a.-c. amplifier of narrow bandwidth tuned at a frequency higher than say 500 cycles per second should be used. The amplifier described by Wilson[4] should show no effects of scintillation when operated at 1080 cycles per second at 0.5-cycle-per-second bandwidth.

Sky Background. Aside from the selection of a specialized observational program there is little that one can do to minimize this very important and troublesome factor. The use of small focal-plane apertures greatly increases the chance of guiding errors and at the same time introduces magnitude errors in star-to-star photometry because of variations in the size of the stellar image with time and position of the star.

The effects of sky background are negligible in importance when measurements of certain emission-line objects are made. Some measurements of the intensity distribution of bright lines in planetary nebulae and in the Orion nebula with a slit photoelectric spectrophotometer have been made at the Naval Observatory. Even when the moon was full, no difficulty was experienced with sky background. The brightness of the Washington "dark sky" is about 18.5 magnitude per square second of arc at 5000 A: a value which is roughly twenty times that found above mountain areas in the western part of the country.

It is possible by the use of one or more devices involving a.-c. techniques[21] to balance out the deflections due to sky background.

The very cases in which these techniques are most desirable, in the observation of faint objects, are also likely to be the cases in which the additional sky noise required can least be tolerated. One also runs the risk of systematic errors caused by faint stars in the additional sky area to which the photomultiplier is periodically exposed.

Dark Noise. It is well known that the dark noise can be reduced by lowering the temperature of the multiplier. Engstrom's data[17] are quite comprehensive and instructive on this point. Also the dark noise increases with the area of the photocathode. N. Schaetti of the Institut für Technische Physik at Zurich has devised a method of producing small cathodes of widely different shapes and sizes with no sacrifice in sensitivity. The possibility of reducing the unused cathode area which produces dark noise by partial destruction of the cathode is a tantalizing problem.

Conclusions

In star-to-star comparisons the errors caused by variations in atmospheric transparency usually greatly exceed those produced by the combined effect of shot noise, scintillation, sky illumination, and dark current fluctuations. If one makes exception to observations of extremely small light intensities, there appears to be little or no advantage in any particular type of photometer provided, of course, it has suitable gain and stability.

For single-star or differential photometry, such as polarimetry, the accuracy should be limited primarily by shot noise; in colorimetry, however, changes in the differential color absorption may be dominant. In polarimetry, therefore, the best signal-to-noise ratio should be obtained when two photomultipliers instead of one are used because the useful signal is thereby doubled as the noise is increased by $\sqrt{2}$. In colorimetry it appears that maximum accuracy can be achieved by Carpenter's[2] a.-c. technique or by some modification of it in which a linear rather than a null method is employed.

In both polarimetry and colorimetry it has been found to be advantageous to use an a.-c. amplifier to indicate very small differences at high gain, and a d.-c. amplifier in parallel with the other to indicate the total effective energy. A dual-beam recorder is a great convenience for observations made in this way.

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THE USE OF PULSE-COUNTING TECHNIQUES IN PHOTOELECTRIC PHOTOMETRY OF STARS

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A Brief History of Pulse-Counting Photometry

FROM THE FIRST DAYS of photoelectric research, attempts have been made to count the individual electrons emitted from a photocathode. As early as 1916, Elster and Geitel[1] demonstrated the basic principle of a pulse-counting photometer using a fast-acting electrometer and a gas-filled photocell just at the point of breakdown into continuous discharge. Steinke[2] in 1926 performed quantitative experiments on fluctuations of photoelectric emission with a similar scheme. Rajewsky[3] carried out investigations using a Geiger-Mueller counter lined with a metal sensitive to the ultraviolet. It is interesting to note that experiments were performed in the thirties at the Cook Observatory with Geiger-Mueller counters sensitive to the visual spectrum.[4]

All the above methods were found in practice to be somewhat unreliable for precise measurements of light intensity. The development of the secondary emission multiplier photocell,[5,6,7] however, furnished a stable device which could indicate, by a sizable pulse at its anode, the emission of a photoelectron. Bay[8] in 1941 experimented with electron multipliers as counting devices for various kinds of radiation. Engstrom[9] made some simple

quantitative measurements by visual counting of pulses appearing on a cathode ray oscilloscope connected to the output of a refrigerated photomultiplier.

In 1946 the writer was struck by the possibility of the application to astronomical photometry of a multiplier photocell used as a radiation counter. As a result of discussion with A. E. Whitford he was encouraged to attempt the construction of an astronomical photometer based on these principles, and an early model

FIGURE 1. Early experiments at Flower Observatory. (Levitt and Blitzstein.)

of a pulse-counting photometer was assembled, using electronic equipment borrowed from the Radio Corporation of America (see Figure 1). This instrument showed considerable promise but was not sufficiently stable for astronomical work. Further necessary development followed, and in 1948 it was possible to begin observations at the Cook Observatory. The writer of this paper observed the light curve of XZ And there and parts of the light curves of three other eclipsing variables. In recent years F. B. Wood and E. M. Lewis have used the same photometer. Cer-

tain modifications and additions have been made that will be described below.

Early in 1948, N. L. Pierce of the Princeton University Observatory initiated the development of a photoelectric photometer along somewhat unorthodox lines. The projected device would employ pulse-counting techniques, digital recording on paper tape, and automatic operation. Through the generous cooperation of Lyman Spitzer, Director of the Princeton University Observatory, funds, materials, and facilities were made available for development work. The untimely death of Pierce in 1950 temporarily halted the work, and the University of Pennsylvania has now assumed the responsibility of completing the photometer and putting it to use. As a fitting memorial the finished instrument will be named the Newton Lacy Pierce photometer.

In England, Yates[10] and Redman have developed and used several pulse-counting photometers at Cambridge. Their results are described in another paper of this symposium.

General Characteristics of a Pulse-Counting Photometer

The nature of the output of a multiplier photocell determines the feasibility of the pulse-counting technique. Consider the anode of a 1P21 cell [11] coupled to the input circuit of an amplifier (see Figure 2).

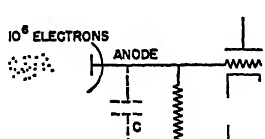

FIGURE 2. Output circuit of multiplier photocell.

As a result of the action of the preceding nine secondary emission dynodes an average burst of approximately 10^6 electrons enters the anode for each electron emitted from the cathode. The capacitance C consists of the stray capacities to ground of the

photocell anode, the vacuum tube grid, and the associated wiring. The anode is charged to its maximum value in a time of the order of the transit time from dynode 9 to the anode (10^{-9} second).[12] It is seen that the capacitance C is charged rapidly and discharges relatively slowly with a time constant RC until the next pulse occurs.[8,13] If we assume 10^6 electrons to enter an anode of total capacity to ground 10^{-11} farad, the peak value of the output pulse will be of the order of 0.02 volt.

The pulses at the anode have a wide distribution in amplitude; measured values show ranges greater than 100 to 1 occur.[8,9,14] This is caused partly by the dependence of focusing (in the dynode system) on the portion of the electrode from which the electrons start, and partly to statistical dispersion in the numbers and direction of emission of the secondary electrons pro-

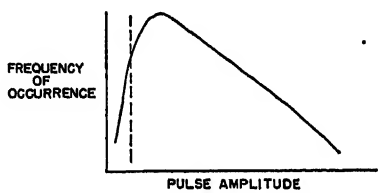

FIGURE 3. Amplitude distribution of pulses.

duced at each impact. Most workers find a distribution similar to that shown in Figure 3. The exact shape of the region to the left of the dotted line is not well known since it is usually considerably influenced by experimental difficulties in counting the smallest pulses.

A matter of great importance in all photoelectric work is the dark current. There are five principal sources of dark emission in the commercial multiplier photocell: (1) thermionic emission from the cathode, (2) thermionic emission from the dynodes, (3) field emission due to the high voltages present, (4) ionization due to residual gas, and (5) leakage over external and internal surfaces.

Thermionic emission from the cathode is by far the most important source in all usual applications.[9] Emission from the dynodes and surface leakage contribute small amounts. Field

emission and ionization are not important in a well-made multiplier operated at low voltages. It is to be noted that the thermionic emission generates pulses that are generally indistinguishable from those generated by photoelectrons. Surface leakage is more or less continuous and generates very small pulses.

In any application of photoelectricity the presence of dark current fluctuations limits the accuracy with which low light levels can be measured. Since thermionic emission is the chief source in commercial multipliers, it is evident that its reduction with respect to the photoelectric emission is desirable. Several methods have been proposed; these include reduction of the surface area of the cathode,[15] use of a high work function cathode,[8] and refrigeration of the cell. The last method, although cumbersome, is the chief method in use today.

A consideration of matters at the anode shows that it would be possible to separate thermal from photoelectric pulses by discrimination against the smaller pulses.[9,15] Figure 4 shows the decrease for one cell in the ratio of pulse count due to a constant light source to dark current count when the number of small pulses counted is increased. This effect varies considerably in magnitude for different cells, depending on the exact shape of the pulse amplitude distribution. It is to be noted that such amplitude discrimination inevitably will reduce the number of counts due to the photoelectrons also. Since the electronic counting devices in the photometer require standardized pulses, it is not only desirable but necessary to provide for pulse amplitude discrimination.

The place at which there is the greatest distinction between the thermal electrons and photoelectrons is at the cathode. The average energy of thermal electrons emitted at room temperature is 0.02 electron volt. The average energy of photoelectrons released by green light is of the order of 1.0 electron volt.[16] It is seen that a retarding potential of less than 0.1 volt near the surface of the cathode would considerably reduce the number of thermal electrons reaching the first dynode. A retarding grid near the cathode might be effective. Obviously it is impossible to modify the internal structure of a commercial cell directly.

The writer discovered experimentally in 1945 that a close fitting metal shield, with an aperture to allow light to enter the cell, maintained at a potential more negative than that of the cathode would reduce the dark current count at room temperatures without reducing the count due to photoelectrons appreciably. The effect of the shield varies with the particular cell used,

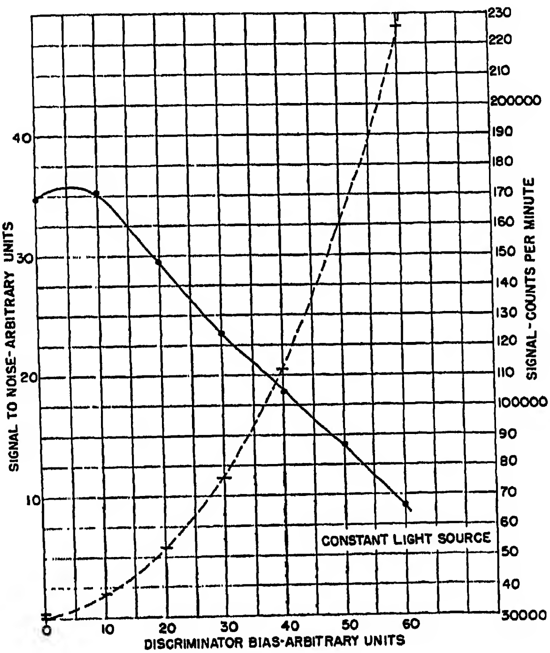

FIGURE 4. Discriminator effect on signal to noise.

but in many cases an effective increase of signal to noise is achieved. Sometimes gains of five or six to one occur. Others[17] have found a similar effect with a shield more positive than the cathode. It is desirable, then, to incorporate such a shield into a photometer.

The question of linearity is of importance in all types of photometry. The pulse-counting photometer is subject to the effects of finite resolving time and blocking due to paralysis of the am-

plifiers for a time interval after the occurrence of a very large pulse. This matter is discussed in some detail by Redman and Yates.

A few miscellaneous characteristics are of importance. Many or all multiplier photocells are subject to microphonics and small drifts. Since the dynode spacing is quite critical, it is evident that mechanical or thermal shock may alter the configuration of the dynodes and change the overall sensitivity of the system. It is well known that multipliers require considerable seasoning under applied voltage to stabilize their characteristics.[15] Also, there is evidence of small steady drifts in the absolute sensitivity of aged

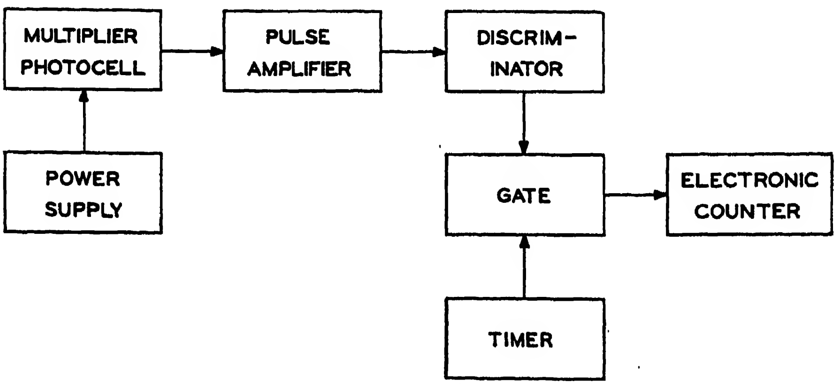

Figure 5. Block diagram of pulse-counting photometer.

multipliers of the order of 4×10^{-4} part per minute.[18] Provision should be made in any photometer for maintaining the voltage on a cell at all times in order to stabilize its characteristics.

Figure 5 is a block diagram of a pulse-counting photometer. The function of the units may be described as follows. By optical means the desired radiation is brought to incidence on the cathode of the multiplier photocell. The output pulses appearing at the anode of the cell are fed into a linear fast pulse amplifier of stabilized gain. All pulses which are greater in amplitude than a selected reference level cause the discriminator to generate a standard pulse. The gate either passes these pulses to the electronic counter or blocks their passage under the control of the

timer. The timing circuits are for the purpose of opening the gate for a specified time interval. The count indicated on the scaler minus the count due to dark current is proportional to the intensity of the incident radiation. It is seen that for accurate comparison of two light sources, the gain of the multiplier, the gain of the amplifier, the level of discrimination and the time of counting must be maintained constant. Herein lie the difficulties in constructing a pulse-counting photometer of accuracy suitable for astronomical work.

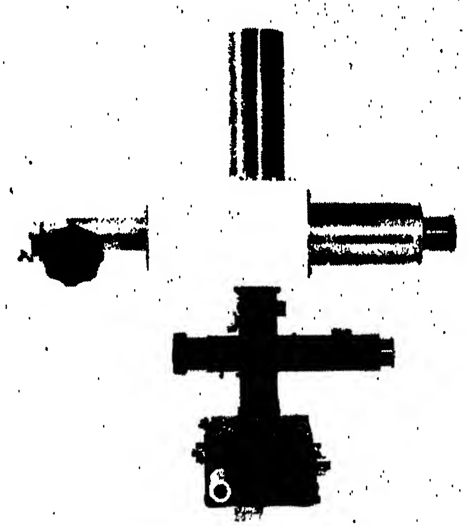

FIGURE 6. Photometer head.

The Pulse-Counting Photometer of the Cook Observatory

The optical features of this instrument are shown in Figures 6 and 7. Some features of this design are peculiar to the Cook Observatory photometer owing to the type of telescope used. It

is the good fortune of the observatory to own a 15-inch siderostat telescope. A siderostat has features which are quite favorable to photoelectric photometry, chief of which are the fixity of the eyepiece and complete shelter of the observer and photometer. It is difficult, however, to equip such an instrument with a finder, and it was necessary to include in the photometer head a low power, wide field eyepiece (3-inch e.f.l.) for location of variable star

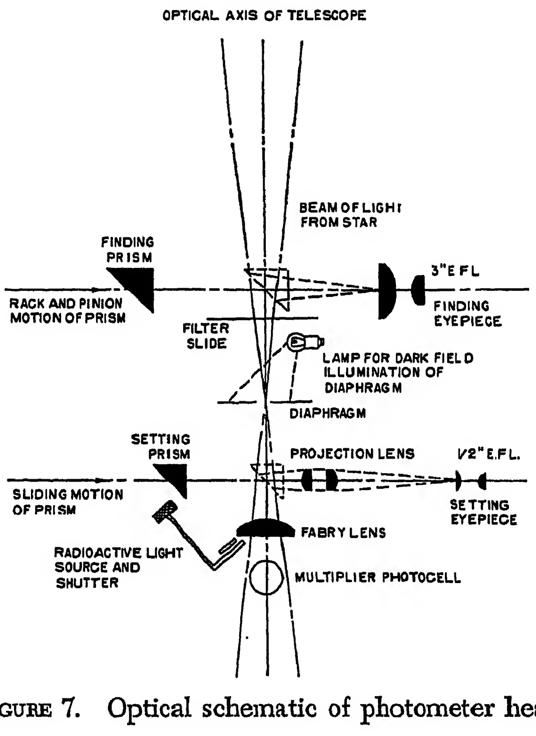

FIGURE 7. Optical schematic of photometer head.

fields and rough centering. For rapid alternation of light from finding eyepiece to photocell a right angle total reflection prism of 2-inch clear aperture is moved by a rack and pinion into or out of the optical axis. This either diverts the light to the eyepiece or allows it to fall down the tube toward the photocell.

Between the finding eyepiece and the setting eyepiece a diaphragm with a small aperture is placed at the prime focus of

the 15-inch objective. Provision has been made for inserting diaphragms of various apertures at this point.

The optical system for setting the star accurately in the center of the small aperture was suggested to the writer by Whitford and has been used at the Washburn and Lick observatories. Just behind the diaphragm and prime focus, a prism can be slid (as described above) into the light beam to divert it to the side. A one to one projection lens (8-mm. double achromat) then projects an image of the diaphragm hole and star out far enough so that it may be viewed by the setting eyepiece (e.f.l. ½ inch). If the diaphragm is slid out of the incoming beam of light a somewhat wider field can be seen and this is useful in centering the desired star.

To see the edge of the aperture against the dark sky background, illumination is necessary. A small 6.3-volt radio pilot lamp controlled by a rheostat is mounted off the optical axis ahead of the diaphragm so that the edge of the hole is illuminated only by diffraction when viewed through the setting eyepiece. It appears as an illuminated circle against the dark background.

Immediately behind the setting eyepiece a Fabry lens of approximately 2-inch focal length and a light tight photocell box are mounted. The opening in the box through which the light enters can be closed by a shutter which is controlled from outside to prevent accidental overillumination of the cell when the photometer is not in use. A radioactive light source* is mounted to one side of the photocell, and a shutter controlled from outside covers it when not in use. This source is quite steady and can be used to check the sensitivity and stability of the photometer.

Provision is made for motion of the photocell mounting from outside to move the spot of light formed by the Fabry lens to the most sensitive area of the photocell. The cell is covered by a wire screen shield which has a rectangular aperture cut in it directly in front of the cathode. This screen is maintained at a potential 45 volts more negative than the cathode.

Since it is necessary that the voltages supplied to the anode,

* A mixture of zinc sulfide and polonium coated on a brass disk.

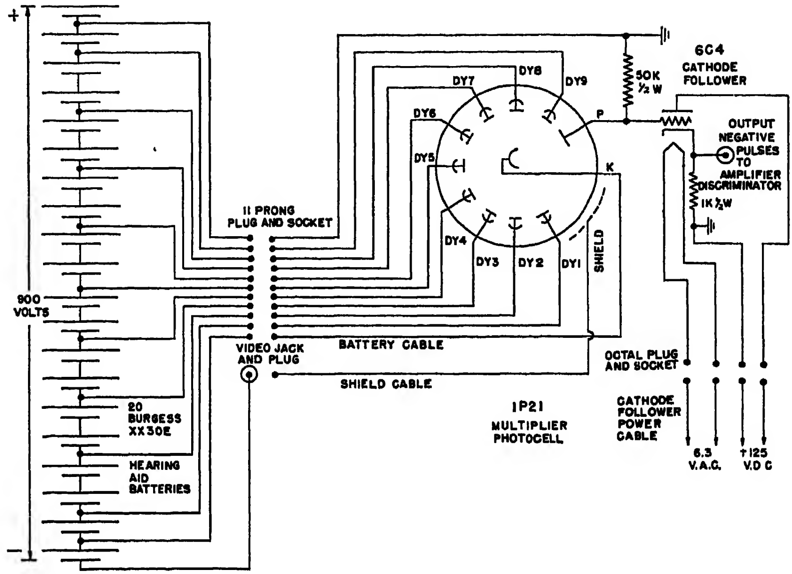

FIGURE 8. Schematic: battery, cathode follower, and multiplier photocell.

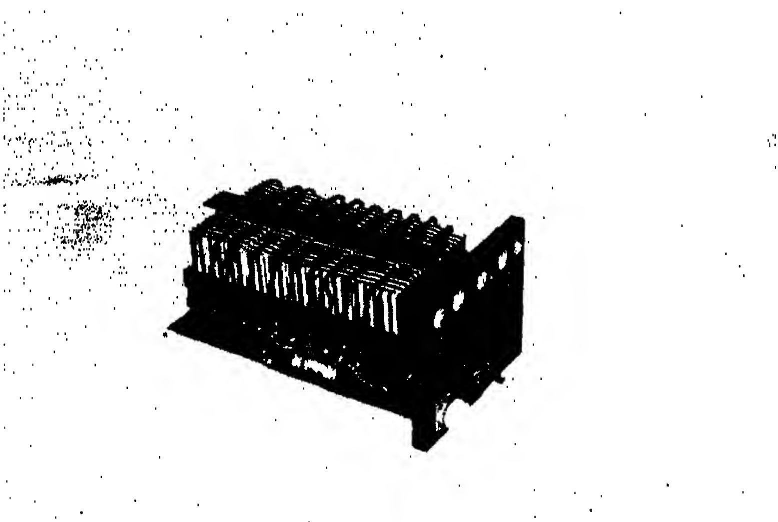

FIGURE 9. Battery case.

cathode, and dynodes of the multiplier cell remain constant, a battery pack is used to power the cell. The current drain is very small (of the order of microamperes), and it is possible to use the small batteries designed for hearing aid and portable radio use. The working lifetime of these, when used for this purpose, is well over one year, and they are inexpensive. It has been found that dipping in hot beeswax before assembling in the battery case eliminates almost completely the damaging effects of inter-

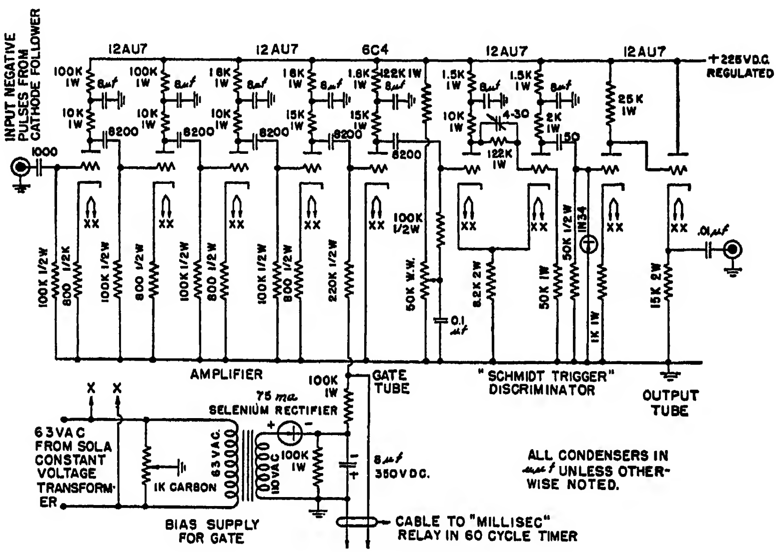

FIGURE 10. Schematic: amplifier-discriminator.

battery leakage under high humidity conditions. The details of the battery case may be seen in Figure 9 and the circuit arrangements in Figure 8. The batteries used are Burgess type XX30E. Twenty of these are mounted on an insulating base of black Bakelite, which serves also as a terminal strip for the various connections. A retaining bar clamps the batteries in position and prevents their motion. Since they are of the plug-in type replacement is very easy. The various connections are brought out to an eleven contact socket and a single contact video jack on the front face of the battery case. Cables which plug into these carry the various

voltages to the photometer head. The voltage per stage used is 90, except for the voltages between the cathode and dynode 1 and anode and dynode 9 which are both 45 volts. The screen is 45 volts negative with respect to the cathode.

The pulse amplifier-discriminator unit is conventional in design. A photograph of the apparatus is given in Figure 11 and a schematic diagram in Figure 10. The basic principles of this equipment are fully covered in references 19 and 20. There are some features, however, which may be pointed out. The ampli-

FIGURE 11. Amplifier-discriminator.

fiers are straight *RC* coupled throughout and thoroughly decoupled from the plate supply. The cathodes are left un-bypassed to improve stability and reduce distortion by introducing some negative feedback. The plate supply voltage is regulated by a conventional series regulated electronic supply. The filament supply is regulated by a Sola constant voltage transformer delivering 6.3 volts a.c. at 50 volt-amperes maximum for an input line voltage variation from 90 to 135 volts. As a consequence the gain of the amplifier is quite constant. The useful bandwidth of this amplifier is 200 kilocycles per second. A considerably better one

could be designed using modern techniques of feedback.[19] However this design is simple, compact and has proved satisfactory for much work at Cook Observatory.

The final amplifier stage is used as a gate tube having normally a large negative bias on its grid (minus 100 volts derived from the bias supply), which is reduced to zero when the timer is started and the Millisec* relay closes. With large negative bias the gate tube is cut off and passes no signal. With zero bias the gate tube acts as an amplifier and passes pulses to the discriminator. This device is of the conventional Schmitt trigger circuit type and has a variable bias control. This allows setting of the pulse amplitude level below which no pulses are counted. The output tube delivers a negative pulse, amplitude approximately 20 volts, at low impedance to drive an electronic counter.

Since the photometer head is necessarily at some distance from the amplifier, the two must be connected by a cable. Even the best coaxial cable has enough interconductor capacity to reduce the peak amplitude and increase the fall time of the pulses if connected directly to the anode of a cell. (See the above discussion for a multiplier photocell and input stage of an amplifier.) The cable capacity may run 10-30 micromicrofarads per foot. This effect can be overcome by various schemes, the simplest of which is insertion of a cathode follower stage between the photocell and the cable to the amplifier. Power for this stage is supplied through a cable from the regulated plate supply and the Sola transformer. The cathode follower can be seen in Figure 6 and a schematic diagram is shown in Figure 8.

The 60-cycle timer (see Figures 12-15) was designed to provide automatic accurate timing of the exposure of the electronic counter to the amplified and discriminated pulse output of the photocell. Such a device is essentially similar in action to a synchronous motor operated time delay relay. A relay of this type† was used in making the initial observations during the winter of 1948-49, but it was found to be somewhat unreliable and not suf-

* A high-impedance high-speed relay manufactured by the Stevens Arnold Company of South Boston, Massachusetts.

† Struthers-Dunn Company. Type PSEHI.

ficiently accurate for this purpose. An all electronic device giving a suitable selection of time exposures with a maximum error of ⅛ per cent of the total exposure was desired. The simplest device of the required accuracy for such purposes is an electronic scaler to which are fed pulses synchronized with the 60-cycle power frequency and which shuts itself off when a predetermined number of pulses are counted. The timer performs these services using a binary scaler plus control circuits.

The use of the power frequency as a time standard was accepted after a careful investigation of the frequency deviations of the power supplied by the Philadelphia Electric Company. A

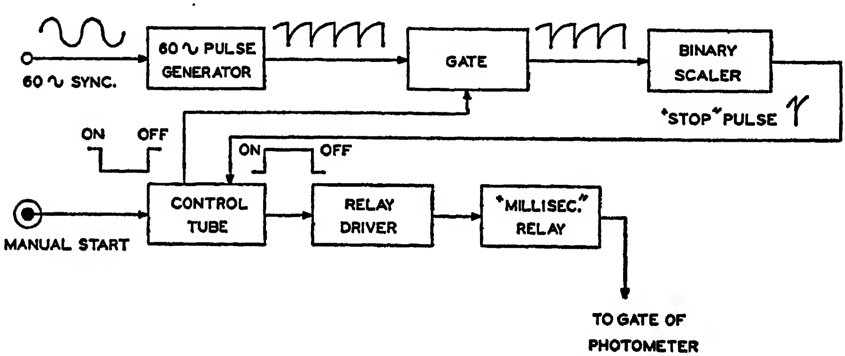

FIGURE 12. Block diagram of 60-cycle timer.

recording made on a Leeds Northrup frequency meter at the Franklin Institute gave a record of changes over a period of many days. It was found that the average absolute error was 0.2 cycle or 0.3 per cent over long periods of time. The maximum error noted was 0.4 cycle; this occurred infrequently and was rapidly corrected. For short periods of time (of the order of 10 minutes) the frequency rarely changed more than 0.1 cycle. It is seen that the power frequency is sufficiently constant for useful work. This is probably true in the case of any large power network.

The action of the timer is as shown in Figure 12. The 60-cycle multivibrator pulse generator runs continuously synchronized with the power frequency. When the observer wishes to make a measurement, he manually actuates an electronic gate

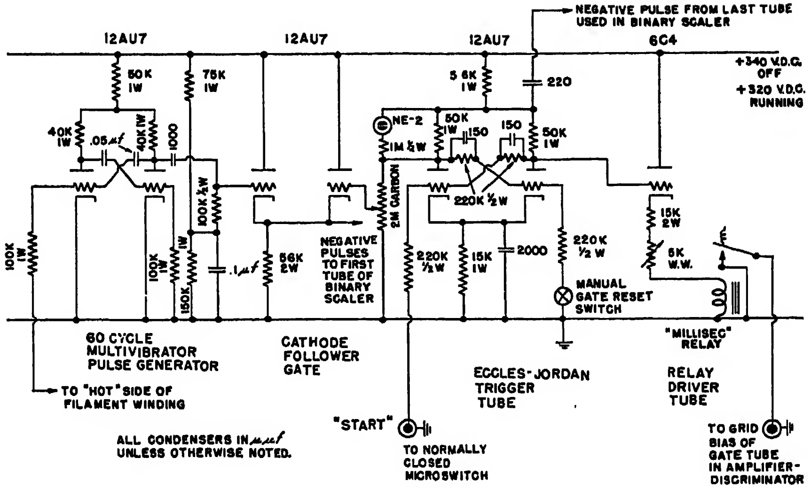

FIGURE 13. Schematic: control circuits.

which allows pulses from the generator to actuate the binary scaler. Provision is made for using the output pulse of any of the last five stages as a stop pulse to close the gate. In this way exposures of 4.3, 8.5, 17.1, 34.1, and 68.3 seconds are available. The exact length of exposure is not important as long as it is constant throughout the observations on a single night. These give a geo-

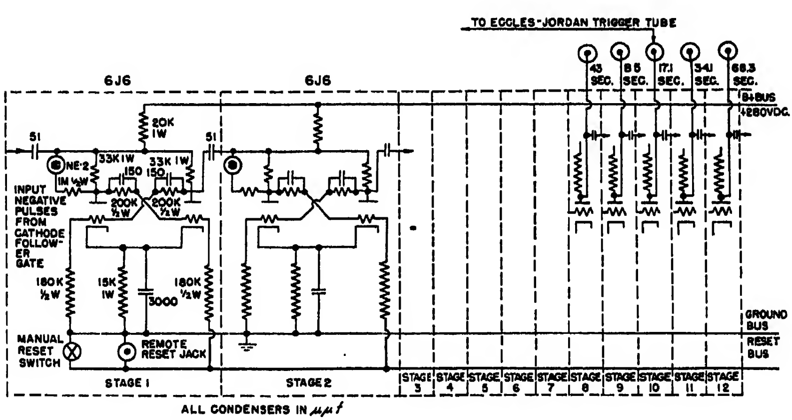

FIGURE 14. Schematic: binary scaler of 60-cycle timer.

metric progression of exposures similar to those on a camera shutter and cover the range found necessary with this photometer.

Some features of the circuitry are of note. Rather than use a single large power supply for both control circuits and binary scaler, separate small unregulated supplies are used for both. Interaction between circuits is minimized in this way.

The 60-cycle pulse generator is an astable multivibrator[21,22] with fixed coupling condensers and grid resistors of values to give

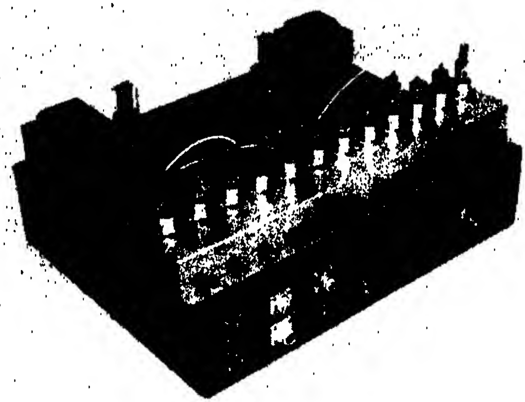

FIGURE 15. Sixty-cycle timer.

a free running rate near 60 cycles per second (see Figure 13). One grid resistor is returned to the "hot" side of the filament circuit. This provides enough synchronization to lock the multivibrator to the power frequency.

The cathode follower gate is a useful circuit for control of the passage of negative voltage pulses. It is illustrated in Figure 13 and is fully described in reference 23.

The Eccles-Jordan trigger tube is a bistable multivibrator[22] which is used to control the sequence of operations. It is manually set in the "run" condition by momentarily opening the con-

nection of one of its grid resistors to ground. This simultaneously sets the cathode follower gate tube in the condition for passing pulses. A negative pulse from the last stage used of the binary scaler resets the multivibrator to the stop condition and the gate simultaneously cuts off the pulses. A quarter-watt neon lamp connected across one plate resistor indicates the state of the trigger tube.

The driver tube and Millisec relay derive their action from the Eccles-Jordan trigger tube (see Figure 13). When it is in the "run" condition the driver tube passes current through the relay. The contacts close and short out the large negative bias on the last tube of the pulse amplifier. It then acts as described above.

The binary scaler is a series of twelve plate triggered scales of two giving a total scale of 4096 (see Figure 14). The last five scales of two have output jacks for use in stopping the counter at selected time intervals after initiation. Quarter-watt neon lamps connected across one plate resistor of each tube indicate the state of the scaler at any instant.

In the early work with this photometer the electronic counter used to record the counts was a modified RCA electronic timer and counter, Type WF99B. This is a 6-decade scaler capable of running at speeds up to one megacycle per second. It is fully described in reference 24. Since the timing features of the device were not needed these circuits were removed. Also the plate supply voltage was lowered to allow cooler operation and a power rheostat was incorporated to control the plate supply. A small voltmeter was built in to allow setting of the voltage. These modifications are necessary to maintain the counter in its operating range. Line voltage fluctuations and heat had considerable deleterious effect.

Recent Modifications of the Cook Observatory Photometer

During the last two years, as use of the photometer continued, several changes and additions were made to increase the observa-

tional efficiency of the apparatus. The original device was in the nature of a pilot model and as such was not necessarily the optimum instrument for its purposes. The acquisition by the University of Pennsylvania of various completed parts of the Pierce photometer made it possible to incorporate some of these into the Cook photometer with resultant benefits. Further, additions to the mechanical and optical arrangements added to the ease of operation.

In order to facilitate variable star photometry in various spectral regions, a filter slide was incorporated into the photometer head. Provision is made for five apertures (allowing for the use of four filters and leaving one blank aperture), which can be successively inserted in the beam from the objective. Filters 1 inch by 1 inch can be accommodated. A detent is provided to insure proper indexing of the slide. The filters at present in use are Corning glass isolating the yellow, blue, and ultraviolet regions. A holder nearing completion will hold interference filters; a second holder, neutral filters of variable densities.

One of the electronic counters, which was designed and constructed at the Princeton University Observatory, was substituted for the original RCA device which had proved unsatisfactory. Some of its features are of interest. The basic circuit used for scaling purposes is a modification of a ring counter designed for the ENIAC.[25] Five of these rings of 10 are arranged in cascade to give a scale of 100,000. The maximum counting rate of these rings is in the region of 200 kilocycles per second for uniformly spaced pulses. However this would not allow a small enough resolving time for our purposes. Therefore the scale of 100,000 is preceded by a high-speed binary scale of 16 having a maximum counting rate of the order of 1.2 megacycles per second for uniformly spaced pulses. The number of binary stages used can be varied by a switch allowing scaling by factors of 2, 4, 8, or 16 to be accomplished. Thus the resolving time is decreased, and it is possible to adjust the count indicated on the decimal registers to a convenient value.

The ENIAC type of ring will allow remote neon lamp indication at distances up to 100 feet or more. This makes it possible

to build the indicator into a small box and to connect it to the relay rack containing the counter by a multiwire cable and plug. In this way the state of the device can be read from any convenient position by the observer. Provision is also made for manual or remotely controlled relay resetting of the counter in preparation for the next count.

Incorporated into this unit are fifty miniature type 5696 thyratrons (one for each digit of a five-digit number), which are part of a printing recording system projected for the Pierce photometer. These thyratrons will actuate solenoids, which in turn will set the keys of a Monroe listing machine.

In an attempt to cut down on the amount of time consumed in going from variable to comparison star in variable star photometry a "triple slide" mounting for the photometer was designed and constructed. This mounting eliminates the necessity for much shifting of the 15-inch siderostat mounting during observation. The efficiency was increased considerably; in some cases 50 per cent more observations could be made per unit time than previously. The unit shows greatest value when the variable and comparison are separated by less than one degree, which angle can be accommodated by the motions provided. A longitudinal movement is available although not necessary for setting on stars. This allows convenient focussing of the photometer or any instrument mounted on the platform of the triple slide. This device can upon occasion be a conveniently adjustable support for any apparatus which is being used at the prime focus of the 15-inch objective.

The Pierce Photometer

The design of this photometer will exhibit certain features: (1) simultaneous dual photometry of close objects, especially eclipsing binaries; (2) digital indication by means of pulse-counting methods; (3) automatic recording by printing on paper; (4) automatic sequencing of operations; and (5) timing in units of decimals of days.

These are aimed at greater accuracy, increase in the number of observations per unit time, and production of data in the most suitable form for analysis.

It has been suggested many times that simultaneous observation of variable and comparison star would eliminate much of the uncertainty introduced by the atmosphere when they are observed alternately. There are difficulties in the use of two photocells, of course. It is necessary that the two cells be similar in such characteristics as sensitivity and spectral response. Further, the two channels of the photometer must have excellent stability of sensitivity for periods of several hours at least. Experience at Cook Observatory has shown that these requirements can be satisfied.

A dual photometer poses some problems in the optical and mechanical arrangements. A design has been adopted which will allow setting of each photocell to receive the light from a specific star in the field of view. The photocell heads are mounted in ways so that they move independently along a line perpendicular to the optical axis of the telescope and intersecting it. Furthermore, the ways containing both heads can rotate about the optical axis. This gives a polar coordinate scheme for locating the cells with respect to the beams of light from two selected stars. A movable wide field eyepiece is provided for rough setting of each unit. In each photocell head an auxiliary eyepiece which can be inserted into the beam just behind the sky background-limiting aperture facilitates precise centering. Provisions are made for the usual filters, radioactive light sources, etc.

The pulse-counting type of indication is selected mainly for its digital nature and also for its ability to integrate accurately the radiation received. Time and labor are saved if the results of a measurement are expressed directly in digital form, and the printing on paper tape of the data stored temporarily in the counters is not difficult.

The automatic recording features are felt to be worth the extra effort. Astronomical photoelectric photometry is at best tedious and time consuming yet requires considerable skill. Since the number of astronomical personnel available is usually small,

any method which releases the observer from strain and increases the number of useful observations per hour is worth while. The projected recording system involves a thirteen digit Monroe listing machine and a printing electromechanical counter manufactured by the Streeter-Amet Company. The counters built at Princeton contain five decades each. Solenoids driven by the indicated digits of each decade will actuate the listing machine keys at the end of a measurement. The machine will print five digits for each counter. The remaining three digits may be omitted or used for any information describing the measurement. The Streeter-Amet printing counter will be driven by a source delivering one pulse every 10^{-5} day (of the order of 0.9 second). It will be set in such a way that at any instant it will indicate the heliocentric Julian day and decimals thereof for the given variable star. The results of both these machines are available for inspection at any time, and the observer can detect any failures immediately.

The automatic sequencing and timing arrangement will make and record observations with a predetermined exposure until the operator sees fit to discontinue operation for any reason. The base of all timing will be units of 10^{-7} day. This time unit is derived from an electronically controlled tuning fork (period 10^{-7} day, frequency 115.47 cycles per second) manufactured by the General Radio Company. This frequency will be scaled down by a factor of one hundred electronically to provide time units of 10^{-5} day. This can be done simply by use of two type GC-10A Ericsson Dekatrons in cascade. By further decimal scaling the counters will be exposed to the output of the photocells for any integral time interval from 1 to 100 times 10^{-5} day.

Advantages and Disadvantages of Pulse-Counting Photometry

Since each of the various techniques in use today has strong and weak points, the choice of the most suitable one depends somewhat on the application planned and the experience of the

designer. The chief advantages and disadvantages of pulse-counting techniques are listed below.

ADVANTAGES

1. Exact integration of fluctuating light source.
2. Direct digital indication.
3. Relative freedom from drift problems.
4. Discrimination against dark emission.
5. Insensitivity to leakage currents.
6. Ultimately higher speed (good observation in one second).

DISADVANTAGES

1. Complexity.
2. Nonlinearity at extremely high counting rates due to finite resolving time.
3. Fairly high power requirements.
4. Bulky equipment.
5. Necessity for more associated test equipment.

It is to be noted that in the light of recent developments such as decade counting thyratrons and transistors that the third and fourth disadvantages need not hold in the future.

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PHOTOELECTRIC INSTALLATION OF THE OBSERVATOIRE DE HAUTE PROVENCE

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THE SENSITIVE ELEMENT of the photometer is a cell of multipliers of electrons constructed at the Observatoire de Paris.

This cell contains an antimony-cesium photocathode of high efficiency, 80 to 100 microamperes per lumen, and nineteen multiplying dynodes of silver magnesium giving a multiplication of the order of 10^8, enough so that a sensitive galvanometer receiving the anode current reproduces the Schottky fluctuations of the photocathode.

Great precautions have been taken to avoid the causes of perturbations of the emerging current. An attempt has been made to diminish the electric field perturbations and the ohmic leakage by giving to the cell sufficiently large dimensions; to exclude the secondary emission of the sides by channeling the electrons and by partitioning the cell. Used without refrigeration the measured performances have been the following:

Multiplication	Dark Current	Fluctuations: Measures $\sqrt{\overline{\Delta i^2}}$
7.2×10^6	1.7×10^{-9} A	0.9×10^{-10} A
15.5×10^6	2.9×10^{-9} A	1.2×10^{-10} A
34.5×10^6	5.3×10^{-9} A	2.2×10^{-10} A

PHOTOELECTRIC INSTALLATION AT THE OBSERVATOIRE DE HAUTE PROVENCE

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THE PHOTOELECTRIC CELLS with nineteen multipliers described by A. Lallemand have been used since 1950 at the Observatoire de Haute Provence. A photometric installation includes a source of high voltage, a photometer, and a recording device.

Source of High Voltage

A cell of nineteen multipliers requires a direct supply of about 2500 volts. The stability of the potential is a function of the variations of the supply circuit and the deviation in the course of a night must not exceed one volt to keep the multiplication constant within 1 per cent. The high voltage is obtained beginning with the supply circuit of 220 volts 25 cycles. A step-up transformer and two valves provide full wave rectification. This current is filtered and supplies twenty-nine tubes of reference (Philips 85A1). A pentode mounted as a cathode follower assures the constancy of the voltage across the twenty-nine 85A1 tubes. Twenty-one precision resistances divide the voltage supply between the nineteen stages of multiplication. This voltage divider is supplied by twenty-nine, twenty-eight, twenty-seven, . . . 85A1 tubes, according to the amount of the luminous flux which falls on the cathode, so that the anode current does not exceed 4×10^{-8} ampere. This is done because we have established that there

is a slow variation in multiplication for anode currents above this value. In summer, an envelope of ice keeps the cell at a temperature of about 2°C. to keep the dark current very low (about 3×10^{-10} ampere).

Photometer

A converging lens forms a Fabry image on the cathode of the cell. A diaphragm of 1-millimeter diameter isolates the star in

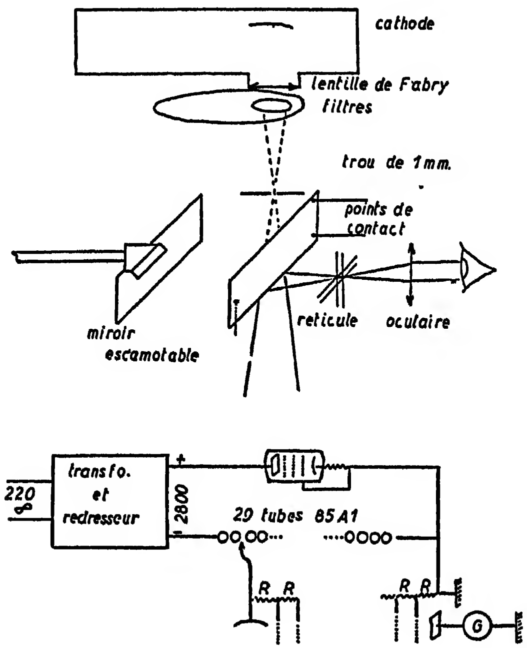

FIGURE 1.

the focal plane. Schott filters (UG 1, BG 12, VG 9, and OG 4) limit the spectral range.

The viewing arrangement permits rapid and precise centering in keeping the maximum field compatible with an exit pupil smaller than that of the eye. The classical means of centering through successive diaphragms of decreasing diameter is a long

operation which we have replaced by the following mounting. The 1-millimeter diaphragm is in the focal plane of the instrument. A retractable plane mirror permits the reflection of the image of the star and of the surrounding field on a lateral ocular. In the focal plane of this ocular is found a square of illuminated wire on a dark background (side of square 0.7 millimeter). By construction and adjustment, the center of the square is conjugate to the 1 millimeter opening with respect to the mirror. It is thus easy to center the star completely while observing the field where the comparison stars are found. The wires are oriented in right ascension and declination. This arrangement which permits a rapid and convenient centering requires a perfect definition of the position of the movable mirror. The mirror is fixed on the control rod by foam rubber; at the end of the travel, the mirror comes to rest against three fixed points which are supported on the edges of the aluminized surface. The three points define perfectly a plane and the flexible mounting sets off again equally the force of contact on the three points. One discovers that the observation and centering of a very faint star is easier under these conditions than through an opening of 1 millimeter.

Two oculars guided laterally keep the centering for long measures.

Measuring Apparatus

Lallemand has shown[1] that the basic noise, Schottky effect, is visible with a galvanometer for cells of nineteen stages. We have verified that its value is near to the theoretical value.[2] The anode current is thus measured without amplification by means of a galvanometer of sensitivity 10^{-10} ampere per millimeter at 1 meter and of period 3.6 seconds. The reading of the galvanometer has been replaced by the photoelectric control of a pen of a Speedomax by the spot of the galvanometer. We prefer this measuring procedure to an electronic assembly which adapts the output impedance from the cell to the input impedance of the Speedomax. A galvanometer possesses the qualities of simplicity,

of stability, of fidelity and of proportionality to a higher degree than electronic apparatus; one is certain that it does not introduce supplementary fluctuations and its band pass is perfectly defined. The photoelectric control is free of oscillation of pumping [hunting] and assures a fidelity of 1/5 millimeter. It has been rendered independent of variations of brightness of the spot.

The distribution of time in the observatory furnishes contacts each 30 seconds; an auxiliary pen marks these contacts on the recording paper. The kind of filter is automatically shown on the recording. An interphone establishes liaison between the telescope and the room situated below the instrument.

The variables RT And, X Tri, RU Cam, RW Mon, and AE Aqr have been studied with this apparatus without any failure of construction or of regulation.

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THE PERFORMANCE OF TWO PULSE-COUNTING STELLAR PHOTOMETERS

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General Remarks

THIS PAPER is a sequel to one published about three years ago, which gave a description of a stellar photometer consisting of a 931-A photomultiplier tube coupled to an electrical pulse-counting apparatus.[1]

Each electron released from the light-sensitive cathode is converted into an avalanche of electrons, which emerges from the photomultiplier as a voltage pulse. By counting the pulses produced during a selected time interval a sensitive measure of the light falling on the cathode is obtained. In outline the procedure is to feed the pulses, after amplification, into a train of "flip-flop" halvers, each of which divides the number of pulses by two, by passing only alternate pulses. After, say, twelve of these, the pulses are slow enough to be recorded by a mechanical counter; or, alternatively, sufficient halvers may be used to record the whole count in a scale of two. It is possible, at the cost of slight extra complication, to arrange the halvers to record on a scale of ten, but this has not been done in any of the work described here. The photometer in its original form was used for about a year on the old Huggins 15-inch refractor and, after experience was gained from this, a second instrument was built, embodying a number of modifications. This has been in use for about

eighteen months. A third photometer has been made for the 3-foot reflector, but is not yet in regular operation.

The photometers have been used for the measurement of stellar magnitude over the range 5^m-11^m. The conditions with respect to both telescope and sky have not been such as to favor an instrument which may be expected to work with the same precision as other photoelectric photometers, and also to perform best at low light intensities. This should be kept in mind when assessing its performance from what follows:

A block diagram of the original photometer is given in Figure 1. The photomultiplier has been used at room temperatures, although provision had been made for refrigeration. The pulse-

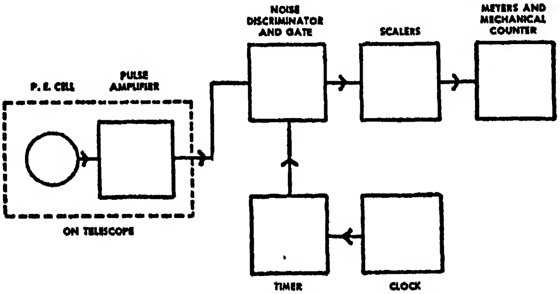

FIGURE 1. Block diagram of photometer I.

counting technique allows one to employ a rather low anode voltage (550 volts altogether), which is a favorable factor in reducing the dark count, relative to the cell response. At this voltage the particular 931-A tube used shows a rather rapid increase of dark count with temperature in the range 15-25°C., but in Cambridge for most of the year the dome temperature is below 10°C. Under these conditions, and with the diaphragm used (diameter 0.′84), the count from the unilluminated cell is usually comparable with that from the moonless sky, and only very rarely, in hot summer weather, has the dark count been high enough to be troublesome. The limiting sensitivity is set primarily by the large diaphragm. With a refractor the chromatic aberration of the objective makes it necessary either to keep the diaphragm large, or to work in fairly narrow spectrum regions and refocus for every change of

filter. In the case of the Huggins refractor, now over eighty years old, poor mechanical condition and the resultant inaccurate following would in any case make a small diaphragm inadvisable. Thus for the work attempted so far, refrigeration would bring little advantage, but it should be remembered that were the apparatus used in other conditions, for example where the sky count is much lower, or in a hotter climate, this simplification would not be possible.

The "noise" from the cell is considerably reduced by removing the anode pin and bringing out the anode lead quite separate from the base. In addition the signal-noise ratio is increased by the "discriminator," which eliminates all pulses below some fixed size, and with suitable adjustment removes a substantial amount of noise without appreciably affecting the signal. The discriminator setting can also be used to vary the sensitivity of the whole instrument, but we consider this inadvisable and prefer to keep this adjustment as far as possible constant.

Before passing to other questions, enquiry may be made as to the reliability of the apparatus. Although not particularly complicated when compared with electronic equipment in common use elsewhere, the instrument is not as simple as most photoelectric photometers, and the question arises whether in general it needs an important amount of servicing care and maintenance, a difficulty which is beginning to be felt with electronic apparatus in other sciences. Our belief is that a well-designed pulse-counting photometer, constructed of high-quality components, should be little less reliable than a domestic radio set, and should be almost as easy to use, despite its high sensitivity. Such a photometer is not quickly affected by vibration or moisture, while accurate readings can be obtained over a wide range of light intensities without instrumental readjustment. Our second photometer, although in many ways an improvement upon the first, has in fact been somewhat the less reliable of the two. We have good reason to regard this as a misfortune not likely to recur, for the most persistent trouble has been encountered in the scaling circuits, and here every breakdown has been traced to a faulty coupling resistor, all the defective components coming from the same original

batch. In all circuits where reasonably constant characteristics are essential, special high stability resistors should be used. The other important source of trouble has been the automatic timer, a convenient accessory which can, however, only justify itself by being perfectly reliable. Three different designs have failed to reach this standard, so that hand timing, which is amply accurate for our purpose, has been adopted.

Linearity of Apparatus

Provided the counting system records every pulse coming from the photomultiplier, there should be a linear, or nearly linear, relation between light intensity and pulse count, subject only to a sampling error at low counts. This last error will appear in one or other disguise when the light intensity becomes very low, whatever the measuring technique used. In our work so far it has been negligible: as a fraction of the total count it has a mean value $1/\sqrt{n}$, and the total count, n, has rarely been less than 10^4.

A more important question is to what extent the apparatus loses pulses at high counting rates, owing to insufficiently small resolving time. The conditions of the problem are here more stringent than one might at first suppose. Although with a steady source the rate of arrival of quanta at the cathode, and hence of pulses at the counter, is practically constant when averaged over large numbers, there is a great variation in the time between individual pulses. The problem is exactly similar to the well-known case of production particles by a radioactive source.[2] The most important point to remember is that if $\bar{\tau}$ is the mean time interval between pulses, then the chance that the actual time interval between two successive pulses will be less than 0.01 $\bar{\tau}$ is approximately 1 per cent, so that if linearity of response to 1 per cent is required, the resolving time of the counting system must be at least one hundred times that needed were the pulses uniformly spaced.

At the brighter end of the magnitude range in which most of our observations have been made, 7^m, and with a filter cutting the

response by a factor about 2, the number of pulses delivered per second by the photomultiplier is about 10^4, so that if we wish to maintain linearity of response to 1 per cent, up to this level, the resolving time of the apparatus must not exceed 1 microsecond. Lamp tests to be described later showed that in photometer I the resolving time was about 10 microseconds, so that corrections for dropped counts had to be applied over most of the magnitude range covered. In common with most workers in stellar photometry, we find that linear instrumental characteristics are a convenience, so that one of the chief objects in building photometer II was to achieve this for most of our working range, by reducing the counter resolving time.

Factors Limiting the Resolving Time

The resolving time of the instrument as a whole is determined in a rather complex way by its various parts, and it seems quite impracticable to work out any theoretical formula to give the counting performance with sufficient accuracy. It is, however, possible to indicate the chief factors which delay the making of a count, following delivery of a pulse by the photomultiplier, not merely because the pulses there come fastest, but also because they are there most irregular.

Restricting ourselves for the moment to the original photometer (Figure 1), we can look for counting delays in the amplifier, the scalers, the mechanical counter, and also in electrical capacities of connecting cables, especially of that connecting the telescope to the counting unit on the floor. We shall not consider the mechanical counter further, for it is not a limiting factor of any importance; by the time pulses reach it, they are nearly uniformly spaced, while the counter itself will run to near its maximum speed without missing anything. In photometer I this stage was approached only when the star brightness reached $5^m.5$.

The amplifier, owing to its finite band width, cannot separate pulses which arrive too close together, and the effective resolving time here depends also on the amplitude of the pulses.

These are not of uniform size and if any are very large they may overload the output stage and paralyze it. In addition, in photometer I the 6 meters of coaxial cable from the telescope to the counting units presented a rather high capacity to the cathode follower, and itself caused pulses to die away rather slowly, with a time constant about 2.5 microseconds. A pulse reaching the first scaler unit decayed to 1 per cent of its initial value in about 12 microseconds. The net effect was to make it impossible to count a pulse for perhaps as long as 20 microseconds after a pulse of unusually large amplitude had been received.

The scalers are built up of "flip-flop" halvers; in their original form the resolving time was about 4 microseconds, independent of pulse amplitude. This resolution was determined by the standard method of using a train of pairs of artificial pulses, the separation in the pair being adjustable. These were fed into the scalers and the pulse pair separation was reduced until the counting rate dropped to one-half of the initial value obtained with wide pairs. The pair separation at this point is taken as the resolving time.

Modifications Embodied in Photometer II

After about a year's experience with photometer I, a complete reconstruction was made, aiming chiefly at a resolving time about 1 microsecond, but including an optical rearrangement as well. Figure 2 gives the new block diagram. First the amplifier was rebuilt with a somewhat greater bandwidth. This was permissible, as the noise voltage generated by the original amplifier is considerably below the average amplitude of the pulses produced by it. The amplifier gain was reduced by a factor about three, to avoid overloading of the output stage by large pulses, and subsequent paralysis. Another improvement was to mount the first scaler unit on the telescope, with as short a connection as possible from the amplifier.

The circuit of the first scaler was modified to reduce the resolving time from 4 microseconds to a measured value 0.6 mi-

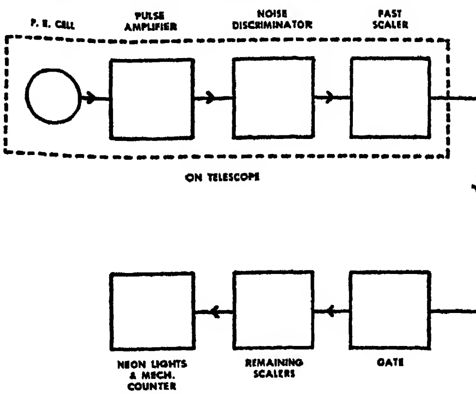

FIGURE 2. Block diagram of photometer II.

crosecond. Figure 3 gives details of one of the four new halvers employed. The change here consisted of building the "flip-flop" with 6J6 (or ECC91) miniature double triodes, which have very low interelectrode capacities and allow the use of small coupling capacities (15 micromicrofarads). The anode resistors were reduced in value, while the speed of operation was also increased by "catching" the grids of the triodes just beyond cutoff by means

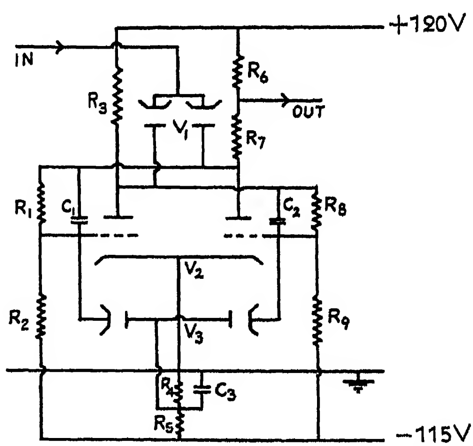

FIGURE 3. Circuit of one of the four halves in the fast scaler. R_1,R_8 470 k; R_2,R_9 680 k; R_3,R_4 15 k; R_5 100 k; R_6 3.3 k; R_7 10 k; C_1,C_2 15 μμf; C_3 0.1 μf; V_1,V_3 EB91 (6AL5); V_2 ECC91(6J6).

of the diodes connected to the grids.[3] The new position for the first scaler reduces by a factor 16 the rate at which pulses have to be transmitted by the comparatively long cable between telescope and observing floor. Furthermore, these pulses are more evenly spaced in time, and are of constant amplitude. It was in consequence possible to dispense with the cathode follower. (The pulses coming from the first unit are with negligible exceptions separated by at least 16 microseconds. The output circuit, including the cable, is equivalent to about 1.5 kilohms in parallel with 500 micromicrofarads, and since the time constant is 0.75 microsecond, the pulses can all be passed without loss.) The remaining scalers are still of the original design.

The improvement aimed at by these modifications appears to have been achieved, as subsequent calibration tests show no significant deviation from linearity up to 10^4 multiplier pulses per second. On this basis the error introduced by assuming a linear response would be less than 1 per cent with stars fainter than $7^{m}.3$, when observed with one of the two standard filters, and less than 3 per cent at $7^{m}.0$. In practice corrections are always introduced before the error amounts to 1 per cent, but the number of stars needing this is comparatively small. Figure 6 shows correction curves for photometers I and II respectively.

Other parts of the apparatus have been reconstructed. The two meters used for showing the final state of the halvers have been replaced by six neon indicator lights. No indicators are used for the four halvers on the telescope, or the first two on the observing floor, since these give merely inappreciable fractions of the total count. At one time the mechanical counter was also replaced by halvers and neon indicators, so that the whole reading was displayed on a scale of two, but this appeared to have no definite advantage, other than being esthetically pleasing, so that the mechanical counter has been brought back into service.

As already mentioned, the automatic timer has been abandoned in favor of hand timing, which for our standard "exposure" of one minute is amply accurate. This exposure time appears to be about the optimum in Cambridge conditions. Shorter exposures might lead to irregularity from scintillation, and might some-

times give such low counts that statistical irregularity would begin to obtrude. Further, as exposures decrease the proportion of time spent unproductively in moving the telescope from one star to another is increased. On the other hand, longer exposures increase the dangers from changes of sky transparency, which at Cambridge are the principal obstacle to stellar photometry.

Besides the electrical modifications, the optical design of the instrument has been greatly changed, partly for convenience, partly to help in accurate centering of the star image in the diaphragm during each exposure. In photometer II the star image can be centered on a crosswire system, where it is inspected by the aid of a 90-degree prism, turned into the beam when required. When the prism is removed, the star is re-imaged at unit magnification on the diaphragm, following which is a Fabry lens and the cathode. The original arrangement for viewing the diaphragm is retained only for occasional verification of the crosswire adjustment. Owing to the mechanical deficiencies of the Huggins mounting, the observer must be prepared to guide during even a one-minute exposure, unless working quite near the Pole, and for this a separate 3-inch guider is used, and collimation with the main telescope is adjusted at the start of each exposure.

Calibration of Photometer

The easiest way to calibrate a stellar photometer is by some completely reliable standard sequence of stars, possessing the necessary wide range in both color and magnitude. At present not even the NPS meets this requirement fully, and another argument against this method is that one has to accumulate enough observations to nullify the irregularities of sky transmission. We have therefore relied on laboratory calibrations to show the counting rate below which the instrument's deviation from linearity is negligible and to give the necessary corrections for higher counting rates.

The first method to be tried employed the principle of the well-known tube sensitometer used in photographic photometry.

A small lamp, run off a large car battery, illuminated a white diffusing screen mounted on a rotating turntable, and thence one of eleven interchangeable diaphragms of accurately known areas, situated at the end of a tube. The tube was provided with an internal stop to cut out reflections from the walls, and at its other end was a ground glass screen. An image of this was focused on the cathode, so as to illuminate approximately the same area as

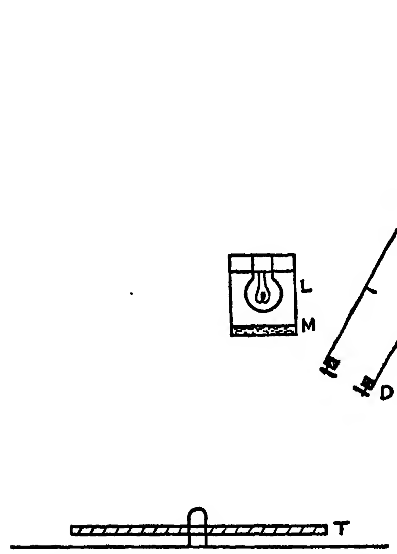

FIGURE 4. Schematic representation of calibration apparatus, Method 1. L, tube containing lamp; M, ground glass diffuser; T, turntable; D, interchangeable diaphragms; S, stop; G, ground glass; C, photocell; F, lens imaging G on cathode of photocell.

used in the telescope, the intensity of illumination being proportional to the diaphragm area, determined geometrically. The setup is shown diagrammatically in Figure 4.

A second method has, however, been more often used, since it has the advantage of leaving the photometer undisturbed on the telescope. A white matt reflecting surface is held about 1½ meters in front of the telescope objective and is illuminated by any of nine independent and approximately equal light sources,

mounted about 2 meters from the reflector, behind and to one side of the telescope aperture. The sources are circular holes in a box, each fitted with a diffuser and lit by a group of lamps enclosed in the box. The apertures can be opened or closed independently of each other, while the lamps are kept running as constantly as possible throughout the measures. The procedure consists of calibrating the apertures singly against one of their number, and then to take readings with two or more apertures combined. If working on a strongly nonlinear portion of the characteristic curve, the observer may need to carry out the reductions by successive approximations.

In early measures the results from the two methods agreed satisfactorily, so that routine checks of the apparatus have been confined to method 2. We should note that several alternative calibration methods which might come to mind are not suitable. For instance, since an image of the telescope lens is focused on the cathode, objective diaphragms alter the illuminated area, which cannot be allowed, since the cathode sensitivity may easily vary from point to point; while altering the illumination will also change the shadowing by the grid in front of the cathode. Rotating sectors should not be used, because at practicable sector speeds the pulses are not thinned out uniformly, but are allowed to reach the apparatus in bunches, which is precisely what one wishes to avoid.

A nonlinearity of the apparatus known to be negligible for the majority of stars observed need not be anything more than a trifling inconvenience, provided the response characteristics can be relied on to stay constant. Experience has shown that this is usually the case, except when some circuit has been deliberately altered. Paradoxically, one of the more serious disadvantages of this photometer is that it nearly always gives an answer. It may be out of order without giving an unsuspecting observer any obvious warning, although the indicator lights generally soon reveal to an alert watcher when something is amiss. In general fairly frequent calibration tests should be made, say once every ten weeks.

Orientation Effect

Eggen has reported a variation with orientation of the sensitivity of a photomultiplier used in a d.-c. arrangement for stellar photometry.[4] He has found that photomultipliers are sensitive to external magnetic fields, and suggests that they may be influenced even by the earth's field. Presumably very slight relative displacements of the anodes, arising from purely mechanical causes, might also affect the total amplification and lead to an appreciable change of response with orientation. We have tested the behavior of photometer II in this respect, especially in the two positions most frequently used in our programs till now, namely near the meridian, north or south, at an altitude around 52°, and have found the change to be certainly less than 1 per cent. We would expect that the pulse-counting technique would be less prone to such trouble than the more commonly used d.-c. methods, since moderate changes of amplification within the photomultiplier make a negligible difference to the number of pulses recorded. True there might be a small alteration due to bringing pulses across the threshold of the discriminator, but we suppose this would be much less than the total effect on the d.-c. response.

Limiting Magnitude

Our working limit until now has been about $11\overset{m}{.}5$. If the star contribution to a reading becomes less than that of cell and sky combined, accuracy begins to fall off rather rapidly, so that unless the night has been both transparent and cool our measures have tended to become less reliable below about $11\overset{m}{.}0$. It has happened that this limit has suited our programs and that there has been no urgent need to extend it to fainter stars.

As already mentioned, it is difficult to avoid a fairly large diaphragm, when using a refractor, unless indeed rather narrow-

band filters are used, and great care is taken with the focusing of the telescope. With the Huggins refractor other deficiencies would put serious practical difficulties in the way of pushing the sensitivity limit more than about a magnitude further, even with the photomultiplier refrigerated. We would, however, expect the photometer to work comfortably to 14^m, were it used on a well-mounted *reflector* of 15 inches aperture, assuming the guiding to be sufficiently good for the diaphragm diameter to be reduced to $0\overset{'}{.}15$, and supposing the cell to be refrigerated.

Photoelectric technique generally now seems to be reaching the stage where the problem of measuring faint stars is primarily astronomical and not electronic; it is a question of using a small diaphragm to cut down the sky contribution as far as possible, which in the last analysis, given a sufficiently good telescope, becomes a matter of how small and how steady the stellar image is. In the competition between photographic plate and photocell the plate has a big advantage when approaching its limiting magnitude, in that it uses a diaphragm, or at least can be regarded as using a diaphragm, which is the size of the star image only. Ultimately, however, the photographic plate is stopped by the same factor as the photocell, not by its own lack of sensitivity, but by the difficulty of discriminating between image and background, when the surface brightness of star image plus sky differs very little from that of sky alone.

We have at present no data giving the relative sensitivity with one and the same photomultiplier, of the pulse-counting arrangement and the more usual d.-c. apparatus. Our results have been obtained with the first 931-A tube which came to hand, but it appears to be a better sample than the average, for in our later experience, still somewhat limited, we have found only about one in ten 931-A's to give as good performance.

Other Possibilities

An alternative method has been worked out by which the pulse-counting technique can be used with a meter or recorder.

This has not yet been given a thorough trial in stellar photometry, but in one form has been applied by M. J. Smyth to a problem in solar spectroscopy. In principle the procedure is to take the pulses from the photomultiplier and to convert them into pulses of a standard size and duration, which in sum give a current proportional to the total pulse count. As tried with a recorder, the pulses from the fast scaler on the telescope were used to fire a single stroke (monostable) multivibrator, which generates a secondary pulse of known amplitude and duration. This in turn switches an accurately determined current into an integrating and recording circuit for the duration of the pulses. The integrating circuit has a time constant of about 0.5 second; the output circuit drives a pen recorder, and effectively integration for time t is obtained by running the recorder for that time. The circuit details are shown in Figure 5. There is a considerable simplification in the electronics of this counting apparatus, as compared with the existing photometer, while no accurate timing is necessary in taking readings. There is also the advantage, common to all continuous recording photometers, that fluctuations of sky transmission are easily detected and may sometimes be smoothed over with little loss of accuracy. A disadvantage of any recording system is that when a large range of brightness is to be covered there must be some accurate means of adjusting the sensitivity of the recorder, if precision is to be maintained toward the faint end of the scale. In this respect the plain counting system seems a little more flexible.

The chief source of inaccuracy in our measures is the sky, and in England outside big cities the responsible agent in most weather conditions is water vapor, rather than dust or smoke. Water vapor is roughly neutral in its effect on sky transmission, apart from well-defined absorption bands chiefly in the infrared, so that it would appear that in this country measures of color could often be made considerably more accurately than measures of brightness, provided the different spectrum regions are measured simultaneously. We should make it clear that such a method would not eliminate sky errors, although we would expect it to reduce them considerably, for the irregularities met so far have

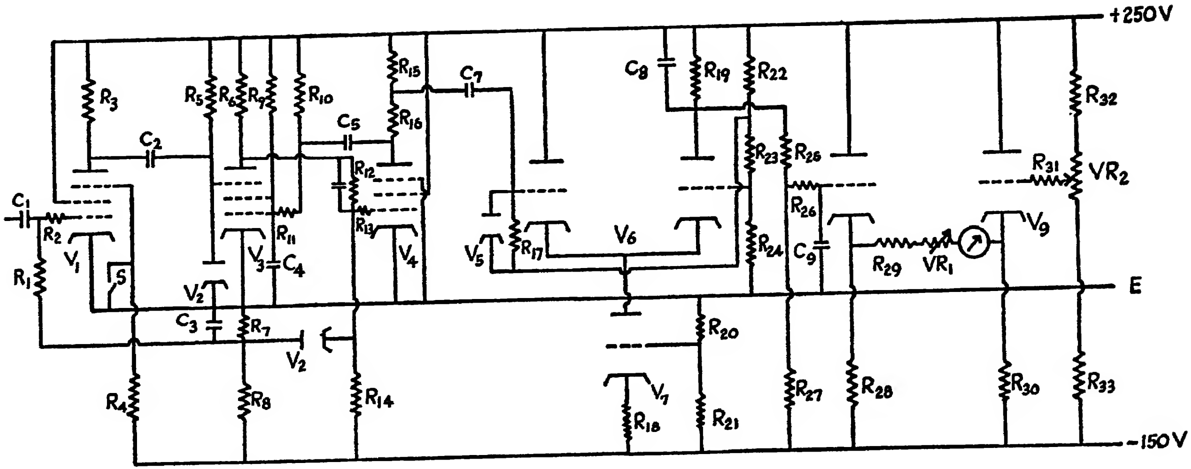

FIGURE 5. Circuit of multivibrator, integrator, and recorder. R_1 220 k; R_2,R_3,R_{15},R_{16} 10 k; R_4,R_{32},R_{33} 180 k; R_5,R_{21} 100 k; R_6 56 k; R_7 18 k; R_8,R_{19} 150 k; R_9,R_{22} 33 k; $R_{10},R_{12},R_{14},R_{25},R_{27}$ 1 m; R_{11},R_{13} 470 Ω; R_{17},R_{26} 470 k; R_{18} 12 k; R_{20} 68 k; R_{23} 4.7 k; R_{24} 15 k; R_{28},R_{30} 22 k; R_{29} 3.3 k; R_{31} 1 k; C_1,C_7 0.01 μf; C_3,C_4 0.1 μf; C_2 20 μμf; C_5 70 μμf; C_6 100 μμf; C_8 0.2 μf; C_9 0.5 μf; V_3,V_1,V_4 VR91; V_2,V_5 VR54; V_6 6SN7; V_7 6J5; V_8,V_9 VR137; VR_1 2 k (sensitivity); VR_2 20 k (set zero); S switch—normally closed—open to set zero.

always been greater in the blue than in the yellow. The problem of constructing an apparatus permitting simultaneous readings to be made in various colors has been under consideration; the solution may lie in the use of some form of low dispersion spectrograph, with wide slits isolating the desired wavelength regions. A similar scheme was tried some years ago by Stebbins and Whitford,[5] but it appears not to have been pursued very far.

Programs and Errors

A program has been completed, measuring 442 stars in the +15° Selected Areas by direct comparison with the Pole, chiefly in order to check the systematic errors of a photographic program in the same areas. The range magnitude is approximately 7^m — $10^m.5$ *pv*. As in all our work, the measures have been made in two colors, with Wratten 5 and 39 filters respectively. The average number of measures per star in each color is a little less than two. We have not aimed at highly accurate individual magnitudes, but have wished to establish an accurate system at +15°, in combination with the photographic observations, and have judged it preferable to spread the observations over a fairly large number of stars, rather than to concentrate on getting very precise magnitudes for a few.

During this work the need became apparent for a comparison of stars of the Seares, Ross, and Joyner Catalogue (used for standards in the photographic work), with the NPS, and of an internal check of the NPS itself. About 100 SRJ stars have been measured as well as all NPS stars down to $11^m.5$ *pg*. The brighter stars, above about $7^m.0$, were observed with the telescope stopped down to 7 inches. The SRJ stars were observed at least twice each; the NPS stars were observed until the standard error of the mean magnitude, judging from internal agreement, was about $0^m.02$.

The color corrections from our working magnitudes to the international *pg* and *pv* systems are of the order 0.1 C.I. In the blue the corrections for the 7-inch aperture are appreciably dif-

ferent from those for full aperture, most probably due to varying transmission across the flint component of the 80-year-old lens. A satisfactory determination of the color correction curve is not easy for negative color indices, since the only NPS stars of this color are bright and are among those most strongly affected by the well-known scale error near 6^m. It is our opinion that the necessity for standard stars of a wide range of color as well as magnitude has so far been rather underestimated by photoelectric observers.

In the Selected Areas program there were generally more than fifty polar comparisons per Area in the photoelectric measures, but only three or four in the photographic measures. Hence the zeros of the photoelectric magnitudes are far more certain than of the photographic, and the differences between the two may be attributed practically entirely to the latter. These differences, in units $0^m.01$, are:

Selected Area	Photoelectric — Photographic *pg*	*pv*
68	−4	−1
70	+1	+3
73	+4	+2
76	+6	+1
78	+5	+5
81	−1	0
84	+5	+4
86	+7	−2
89	+2	+2
All	+2	+2

The mean for all Areas is satisfactorily small, and the scatter in individual values is about what might be expected from the irregularity of the Cambridge sky. Two separate reductions of the data were made, the first giving stars equal weight and neglecting extinction (the Areas having been observed at the same altitude as the Pole), the second weighting according to the number of observations, and inserting small extinction corrections. According to which method was followed there were individual changes in the above figures up to $0^m.03$, but the mean result for all Areas varied by less than $0^m.01$ in both colors.

We have removed the supposed systematic errors of the photographic measures, Area by Area, using the above figures, and then computed the standard error of one photoelectric observation from the differences between each photoelectric value and the mean photographic value. In this it was assumed that the internal agreement of the photographic measures, after correcting their zeros as just mentioned, gives an accurate measure of their accidental errors. The total number of photoelectric observations used in this way was 734 in the blue, 692 in the yellow, and the number of photographic magnitudes, *pg* or *pv*, was 409. The result was that the standard error of one photoelectric observation is $0^m.076$ with the blue filter, and $0^m.056$ with the yellow.

We can make another estimate for the error of one photoelectric measure from the work done at the Pole. For most of this the two stars 88°105 and 88°131 were used as standard, 88°11 was used occasionally, and 88°112 for brighter stars. Seven stars have twelve or more measures each relative to one or other standard (generally one measure only per night). From the interagreement of these we find standard errors running from $0^m.03$ to $0^m.08$. Weighting the stars equally, we deduce a standard error $0^m.05$ for one blue measure, and $0^m.045$ for a yellow. If we take 122 measurements for 14 NPS stars in the range $7^m.15$ to $10^m.98$ (some of the material overlapping with that just mentioned), and take the original NPS magnitudes as exactly correct, the standard error per single measure is $0^m.06$ blue and $0^m.05$ yellow. In the Pole work all the stars are fairly close together in the sky, while for the Selected Areas they were being compared at large distances, about 75°. We would expect smaller errors in the first case, if sky irregularity is the dominating factor, and this is what is found. In every case the error for a yellow observation is smaller than for a blue.

In estimating these errors we have assumed the reference star reading is perfectly accurate, and spoken as though all the error were thrown on the other star. Strictly speaking the error is of a magnitude difference from a set of readings of the form (standard*, other*, standard*, sky). If the two stars are far apart in the sky there are two sky readings.

Comments

(1) Although the primary objects of these programs have been attained, and although in particular we can be well satisfied with the systematic differences between photographic and photoelectric magnitudes in the Selected Areas, we must confess to some disappointment in the size of the accidental errors. They refer to all-year-round photometry, with perhaps too conservative a policy with regard to rejecting discrepant readings, and doubtless a better showing would be made from specially selected nights, for there is a fairly clear correlation between unusually large residuals and the state of the sky as judged by the naked eye, or by the imminence of clouds. In England, unfortunately, it is impracticable to confine photometric work to moonless nights judged to be of first class transparency, as the number of these is far too low. Results from the first year of observations, mainly with photometer I suggested a smaller mean error, about two-thirds of that found now. The only explanation we have to offer is the undoubted fact that the weather of the second year was persistently inferior to the first.

(2) The self-consistency of readings in lamp tests is much higher than on stars, although we have made no special effort to control the lamp brightness precisely. The mean error per reading in such tests is usually near $0^{m}_{.}01$. Also we find that rapidly repeated readings on one and the same star (which in general we have deliberately avoided) tend to give much better self-consistency than readings repeated at longer time intervals. In comparing neighboring stars it is to be expected that the faster the readings can be made the more accurate will be the results, provided the increased speed does not of itself introduce extra error into the work.

(3) All high-voltage supplies in the instrument are stabilized, but we nevertheless find a serious change of sensitivity with mains voltage. Experiments with photometer III, which is not yet in regular use and has not been discussed in this paper, show that

the effect comes through the filament heaters of the amplifier, including the discriminator. The gain of the amplifier rises with filament voltage so that additional pulses are brought over the threshold of the discriminator, while the threshold itself may at the same time fall slightly, so that the two effects tend to reinforce each other. The incoming supply from the mains, at present liable

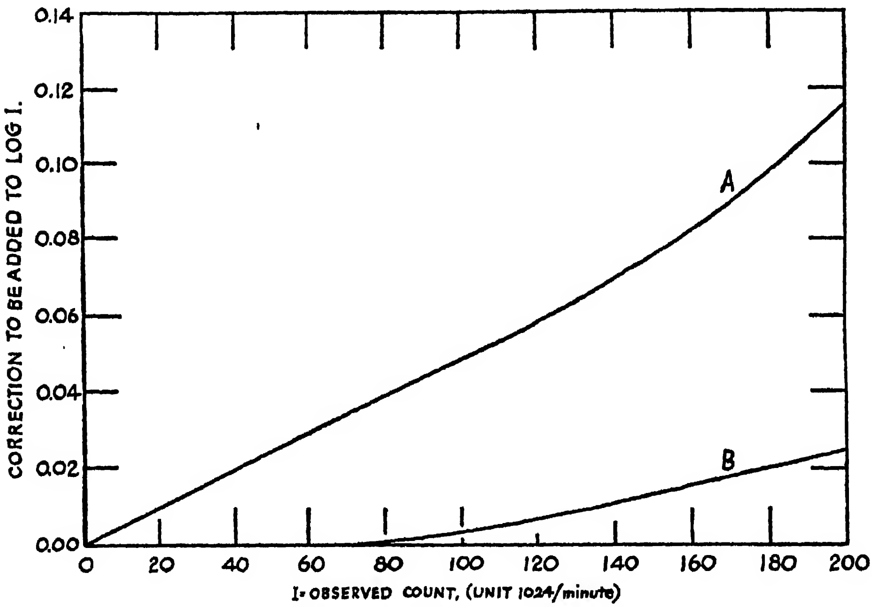

FIGURE 6. Correction curves: A, for photometer I; B, for photometer II. The counting unit is $2^{12} = 4096$ photomultiplier pulses, and the curves refer to an "exposure" of one minute. A 7^m star with filter in these units gives about 100 per minute.

to very large voltage and frequency changes, is therefore fed through a Variac transformer, adjusted by hand. We are not satisfied with this arrangement, since not all the short-period fluctuations are smoothed out, and are at present devising a more thorough control of the filament heaters.

(4) The Fabry (photographic) method as carried out in South Africa by several observers, including one of the present

writers, has given errors per exposure less than one-half than found here; in the best cases much less.[6] The controlling factor is presumably the sky rather than the instrumental method. While the Fabry method is probably "as good as the sky" almost anywhere, it does not go to such faint magnitudes as the photoelectric method, while corrections for the light of the sky are more difficult to make, since the photographic emulsion's response is not linear, and is not constant from plate to plate. On the other hand, for brighter stars the Fabry method is equally quick, and probably equally accurate, while it uses very simple and reliable apparatus.

South African experience, notably at the Cape Observatory, has also shown that in-focus photographic photometry of stars can yield a standard error about $0\overset{m}{.}05$ per star per plate.[7] This method has its disadvantages, by now fairly well known, but since it is incomparably more economical of time at the telescope and again uses simple apparatus, for any large-scale magnitude program it is generally to be preferred to photoelectric photometry, however much the latter may excel in special problems. The advantages of photography become still greater if accuracy is limited by the climate.

We wish to express our thanks to other members of the staff of the Cambridge Observatories, especially to Dr. A. Beer, for help with the photoelectric observations and with all stages of the photographic program.

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ON THE USE OF SERVOMECHANISMS IN PHOTOELECTRIC PHOTOMETRY OF STARS

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PHOTOELECTRIC PHOTOMETRY of stars such as it is practiced generally, with phototube, amplifier, and recorder approaches much more absolute photometry than the photographic and visual methods. The advantages of the photoelectric method are the high stability of sensitivity and the linear relationship between brightness and measured deflection, which can be realized by proper design. Nevertheless, these improvements do not eliminate the necessity of doing the measurements relatively. In the past, by applying the null method, good relative measurements could be obtained even with a poor photometric instrument such as the human eye. It would seem very promising to combine the advantage of the null method with the excellent properties of the phototube. Moreover, in that case, the phototube can be made to perform the null setting itself by means of suitable electronic amplifiers and an electric motor. Such an arrangement, which should be termed a servomechanism, measures essentially the ratio of two light intensities.

In astronomical practice the application of this type of photometer meets the problem of directing the light beams of two stars, which may have all possible distances and position angle, properly into the instrument. This requires, in general, a careful adjustment which takes much more time than the setting of the telescope on a single star. The use of such a photometer is limited, therefore, to applications where the adjustment is not often

repeated, such as obtaining continuous light curves of variable stars or measuring polarization with the two images formed by a spar prism. Since 1950 at the Leiden Observatory experiments were performed with photoelectric null-method photometers, which led to the development of a useful variable star photometer.

The essential difference with the straightforward photoelectric photometer lies in the fact that an optical quantity is measured instead of an electrical quantity. The function of the phototube and following amplifier is reduced to giving a signal which indicates how the intensity of one of the star images has to be changed in order to make it equal to that of the other.

If each star has its own phototube, extreme care is necessary to get and to keep the sensitivities of the phototubes accurately matched. Therefore the more practical method is to direct the light beams intermittently to the same phototube, in which case the signal is the resulting a.-c. component in the photocurrent. In this method the stability of sensitivity of the phototube and the linearity of the amplifier are of no importance, because changes in these characteristics influence only the sharpness with which the equilibrium position is reached and not the equilibrium position itself.

On the other hand, the optical system, which concentrates the star light on the phototube and which contains the equalizer, must be very stable, and the calibration of the equalizer by which the ratio of the intensities is found must be accurately known. As the two star beams pass through the optical system along different pathways, differences in transmission may be expected, affecting the reading of the intensity ratio. In other words, in general a zero point error of the measured magnitude difference is present. This is a disadvantage with respect to the direct photometer, where the light of the two stars that are compared follows exactly the same path by pointing the whole telescope alternately to each star. It has to be accepted, however, in any method other than that of resetting the telescope. To keep the zero point error small, proper design and cleanness of the optical components are extremely important. Moreover, within the above-mentioned limits

of application the error can be kept reasonably constant and then is not harmful. The magnitude scale depends on the properties of the equalizer and is intrinsically stable. Its calibration can be established once and for all with the degree of accuracy which is desired.

Besides the already mentioned systematic errors, the at random distributed errors, caused by atmospheric turbulence or by noise of the photocurrent, have to be considered. As in a direct photometer these can be determined from the time constant of the instrument.

Although the theory of servomechanisms has been developed for very complicated systems, in this particular case that theory is simple, because the requirements of the system with regard to speed of response and delivered power are low. Instead of the third order, or still higher order, differential equation usually required to describe the behavior of servosystems, in this case a second order equation is adequate.

It is usual to express the behavior of the system in terms of the position angle of the motor shaft. Let Θ_i be the position angle which the shaft should have according to the intensity ratio of the stars, and Θ_0, the position angle which the motor shaft actually has. Therefore, the motor is out of position to an amount $\varepsilon = \Theta_i - \Theta_0$, the error angle. As the motor is mechanically linked to the equalizer, there is a fixed relation between the position angle of the shaft and the transmission factor of the equalizer. To the error angle ε corresponds a difference in intensity of the two beams, which alternately enter the phototube. This gives rise to a certain a.-c. component in the photocurrent, which, after amplification, is applied to the motor input terminals as a signal $K\varepsilon$. The coefficient K is a product of the change of transmission factor of the equalizer per unit of shaft position angle, of the intensity of the star light, of the sensitivity of the phototube, and of the gain of the system of amplifiers.

In general, the motor has a speed of rotation which is more or less proportional to the signal. Since it is desirable that this proportionality is fulfilled over as big a range as possible, it is

usual in cases where the motor lacks this property to enforce it by such methods as magnetic damping or velocity feedback. In this case, where only small power must be delivered by the motor and also the speed of rotation is most of the time low, a low-inertia armature can be used and a good linearity of the speed to signal characteristic can be realized. Consequently, the motion of the system can be described by the formula:

$$f\frac{d\Theta_0}{dt} = K\epsilon = K(\Theta_i - \Theta_0) \tag{1}$$

where f is the speed to signal coefficient of the motor. The equation expresses that the behavior of the system is the same as that of a direct photometer having a time constant f/K. It is curious, however, that the time constant depends on the brightness of the stars, which is contained in K. Unfortunately the behavior of the photometer cannot be described by a formula as simple as (1).

To let the motor rotate, signals are required of the order of some 10 volts at least, and a considerable amplification has to be applied to raise the smallest error signals to such values. The fluctuations are amplified along with the signal; this results in the blocking of certain stages of the system of amplifiers, unless the bandwidth of this system preceding these stages is sufficiently narrow. A reduced bandwidth, however, naturally introduces a time lag, which means that it takes some time to build up the signal at the motor terminals in accordance to the error signal given by the phototube. Let the actual voltage at the motor input be V, then the effect of the time constant τ of the amplifier can be described by:

$$\tau\frac{dV}{dt} = K\epsilon - V \tag{2}$$

which, together with the formula for the speed of the motor:

$$V = f\frac{d\Theta_0}{dt}$$

gives:

$$\frac{d^2\Theta_0}{dt^2} + \frac{1}{\tau}\frac{d\Theta_0}{dt} + \frac{K}{f\tau}\Theta_0 = \frac{K}{f\tau}\Theta_i \tag{3}$$

Now the characteristic equation is that of an oscillator and for proper functioning the relation $f = 4K\tau$ must be fulfilled, corresponding to critical damping. In that case the response of the instrument is such as defined by a time constant $2\tau = f/2K$.

On the basis of equation (3) the design of the electronic parts of the system might be planned. Experience has shown that the conditions of the theory need only approximate fulfillment. Especially deviations resulting in underdamping can be considerable before they are dangerous.

It might be thinkable to aim at a type of response, such as is given by formula (1), which is possible if the time constant of the smoothing filter can be small. This, for example, might be appropriate in the case of polarization measurements, where the fluctuations in the intensity ratio of the two images, given by a spar prism, must be practically independent of atmospheric turbulence, and, on the other hand, a very light and sensitive servomotor can be used for rotating a small piece of compensating glass. In principle the null-method photometer for variable stars gives no increase of accuracy, compared with the direct photometer, provided allowance has been made for the effective observing time in both cases. It is only the turbulent elements of the air, very high up in the atmosphere, which alter effectively the light flux received by the aperture of the telescope from a certain star. Therefore, the intensities of two stars are varying independently of each other.

In the course of the experiments three null-method photometers have been constructed, the first being the most primitive one and the others are modifications based on the foregoing experience. In the following, a short discussion shall be given of the most essential methods or components which have been tried.

Common to all constructions was the type of equalizer, for which a wedge of neutrally absorbing glass was used. This has proved to be an excellent device with several advantages.

The transmission factor is an exponential function of the scale. As a consequence the light curves are registered proportionally to magnitudes, which can be very convenient. A single factor is sufficient to reduce the readings to magnitudes. It is

often possible, therefore, to study the characteristics of light curves directly from the photometer tracings and to apply the magnitude factor only to the extracted results. In the case of big series of observations this means an important saving in time otherwise spent in reductions of readings and plotting of light curves. The only objection against the use of a wedge might be that there exists no glass which is really neutral. In practice it is possible, however, to find glasses which are sufficiently neutral within the wavelength regions to which photoelectric measurements normally are confined. Consequently, since the correction factor depends on the effective wavelength, and also, because it depends on the way in which the light beam passes the wedge, it is essential to calibrate the wedge under exactly the same conditions as during the actual measurements. Obviously, the most suitable method of calibrating is to use the photometer itself, with the light switch fixed in one position and one diaphragm closed, on the comparison star as a direct photometer, by connecting the phototube output to a d.-c. amplifier with well-known characteristics.

The light-switching arrangement can be simple in the case of one phototube. The lens which, as usual, forms an image of the object glass on the cathode must have an aperture, wide enough to catch both stars which are to be compared. This is a problem when a 931A photomultiplier is used, on account of the poor accessibility of its cathode. It has been solved by using two crossed cylindrical lenses, forming an elongated elliptical image of the object glass, which can be fitted into the rectangular cathode area. In this way the aperture can be made big in at least one direction, which is sufficient. The light switch itself consists of a plate with two small holes, the diaphragms, which oscillates in the focal plane of the telescope in such a way that each star at a turn can pass through. This method eliminates in an elegant way the effect of the sky background light, for this light, shining continuously through both diaphragms, adds nothing to the a.-c. error signal. Of course, one has to be sure that such a component is not introduced by other stars.

A much more complicated optical system is required when

two phototubes are used. In view of the greatly increased difficulties, against a small improvement of the results, which is merely a doubling of the weight, for a simple photometer the one-tube method is preferable. In the latest construction, however, the method with two phototubes was used, and the switching arrangement was as follows.

The diaphragms have a fixed position in the photometer, and the stars are centered into them by adjusting the distance with a system of reflecting prisms and by adjusting the position angle by rotating the photometer. Two other diaphragms are used, which receive sky background light only. All diaphragms have the same size and are arranged on a line, with distances between them as is required by the switching system. The latter is placed behind the diaphragms and consists of a system of small reflecting prisms, all of the same make and size, mounted together on a slide. The prisms are arranged in such a way that the light coming from the object glass is alternately directed to the one or to the other phototube. If now the slide is shifted over the dimension of one prism, each prism is replaced by its neighbor, with the result that all light beams change direction. In other words, the effect is as if the phototubes were interchanged.

Let the diaphragms be numbered I, II, III, and IV. In I star s_1 is placed; moreover an amount h of sky light is passing through together with the star light. The second diaphragm, II, receives only sky light, h. In front of diaphragms III and IV the wedge is placed and, therefore, the light, entering these diaphragms, is weakened by a factor w, which depends on the displacement of the wedge. The intensity of the light in diaphragm II is then $(s_2 + h)w$, if s_2 is the intensity of the other star, and finally the light entering diaphragm IV is hw. A certain phototube sees, with the slide in one position, the diaphragm I and IV and, with the slide in the other position, diaphragms II and III. The amplitude of the light variation is, therefore, $s_2w - s_1$, which becomes zero when $s_1/s_2 = w$. Thus the sky background light has been eliminated. The other phototube gives the error signal, in the same way, independently. It may be remarked that many other systems of commutating the light are possible.

The electronic system has been developed more or less empirically. As a rule the successive changes or improvements were an approach toward a better fulfillment of the conditions as prescribed by theory. Remarkable was the tendency in the frequency of switching, which was successively 50 times, 20 times, and, in the two-phototube system, once per second. The reason for this was, that with lower frequency the character of the error signal in the photocurrent can be more easily studied and controlled. For example, the strong peaks in the photocurrent, which occur at the moments of transition, were affecting the signal in the 50-cycle system; they were practically excluded from the signal in the 20-cycle system, and completely removed in the slowest system.

The best method of smoothing the error signal is the use of commutating contacts, which are attached to the optical switching device. After the a.-c. signal, from the output of the pre-amplifier, has been converted by these contacts into a d.-c. signal, it can easily be smoothed by means of RC filters. Since the contact is broken during the transitions, the transition peaks are not affecting the signal, provided the time of response of the pre-amplifier is sufficiently short.

How small the fraction of the total time, occupied by the dead time, can be made, depends on the ratio of the frequencies limiting the bandwidth of the amplifier. On the other hand, the difference of the limiting frequencies, or the bandwidth of the amplifier, determines the amplitude of the noise peaks and the condition that these peaks should not be clipped off, fixes the maximum gain of the amplifier. It is clear that more gain and a better time efficiency can be reached when the switching frequency is low.

Apart from the electronic side of the problem, the mechanical inertia of the optical switch gives less difficulties with a low frequency. In the 20 cycles per second system the little plate with the two diaphragms was put in a rectangular motion, by means of a multivibrator, with reasonably short transition time. In the once per second system the slide with the prisms, which

is rather heavy, was given a jumping to and fro motion by means of a cam, driven by a motor.

Not much need be said about the pre-amplifier. Where it is not required to measure exactly, quantitatively, a photocurrent and, since condenser coupling is applied between phototube and amplifier input, it is permitted to use a very high input resistance. Therefore, in general, a voltage amplifying pentode tube, followed by a cathode follower, is adequate. Also the design of the amplifier, which follows the filter, offers no special problems. The filtered signal is already at a level where no troubles are encountered from the drift of either a d.-c. amplifier or of a d.-c. to a.-c. converter stage, using diodes.

The servomotor is an important component of the apparatus. The simple two-phase a.-c. induction motor, which was used in the beginning, gave usable but not beautiful results. This is a consequence of the nonlinearity of the speed-to-signal characteristic of the type of motor. A fairly big minimum signal is required to start the running of the motor; from there the speed increases rapidly with the signal and then reaches a maximum value, nearly 50 revolutions a second, above which the speed cannot increase, no matter how big the signal is. This unfavorable characteristic is but little improved by applying magnetic friction. The effect of this shape of characteristic is that the registration becomes a broken step line when control stiffness is low. With high control stiffness the result is a zigzag line with exaggerated noise peaks. A reasonable performance can be obtained only by careful adjustment, which, however, can easily be disturbed by changing conditions. Moreover it is not easy to combine a good reproduction of noise with a reasonable short time for a full-scale run.

More satisfactory results can be obtained with a d.-c. motor, which has been used in the photometer with two phototubes. With the armature connected between the cathodes of the power tubes (fed from transformer windings) the system is not more complicated than with the a.-c. motor and an excellent linear speed-to-signal characteristic is obtained. To close the loop, it should be mentioned how the motor is connected to the wedge.

Originally the motor was mounted in the photometer itself and was coupled to the wedge by some gears and a friction coupling. The latter prevented jamming if the wedge was driven to an extreme position. The registration of the light curve was obtained by fixing a contact arm to the wedge, which, sliding over a potentiometer, gives a signal which was led to a Brown recorder.

In the two-phototube photometer the servomotor is driving a registering pen in a device placed on a table. The connection with the wedge is made by means of an auxiliary servosystem in which selsyns were used for misalignment measurement. Of course the reduction factor of the speed, from motor to wedge, has to be considered carefully in connection with the other characteristic quantities of the instrument. Although the latest photometer has grown out to a complicated system, involving three motors and two selsyns, it has proved to be a reliable instrument. In about five hundred hours of observation with it, hitherto not a single repair had to be made.

The accuracy of the results is satisfactory, especially when the short period fluctuations are considered. When, in registered light curves, readings are made of one-minute intervals and the root mean square of the deviations of these readings from a smoothed light curve is determined, sometimes it is found to be as low as 0.002 magnitude. This is the case when observing seventh magnitude stars with the 16-inch telescope of the Leiden Southern Station to which the two-phototube photometer is attached. Moreover a color filter transmitting the light with a wavelength between 4000 and 5000 A was inserted, which reduced the light by about one magnitude. Under similar conditions a single phototube photometer gave a spread of 0.005 magnitude.

For the root mean square of the fluctuations in the light of the bright stars, which are caused by atmospheric turbulence, when observing with a 12-inch telescope the following value has been given:*

$$\sqrt{\overline{\Delta I^2}} = 4.5 \times 10^{-2}\, I \sqrt{f_0} \tag{4}$$

* H. L. Johnson, *Ap.J. 107*, 34 (1948).

where I is the intensity of the star, and f_0 is the bandwidth of the photometer. Accordingly, when the time constant of the photometer is one minute, corresponding to $f_0 = 0.0026$ herz, the r.m.s. of the fluctuation is 0.0023 of the signal itself. In the magnitude difference of two stars we may expect fluctuations of 0.0035 magnitude. Considering the coefficient in the formula as a mean value, and also the difference in size of the object glasses, the agreement with the observed value of 0.002 magnitude is satisfactory.

How it is with the long period stability is difficult to say. As has been said already, this depends completely on the perfection of the optical system. A test, such as comparing on many nights two stars of known constant brightness, would take too much valuable observing time. However, also from the light curves of a regular variable star some idea can be formed concerning the stability of the zero point of the magnitude scale. With the latest photometer the systematic errors seem to be well within a hundredth of a magnitude.

The outstanding advantage of the instrument is its high degree of automatization and the corresponding saving of labor and strain. Once it is adjusted for a pair of stars, the observer can switch on the power line and then keep himself busy with some other work. With the telescope used, only about every half-hour the guiding had to be checked. In this respect no comparison is possible with the direct photometer, with which tiredness is unavoidable after some five or six hours of continuously manipulating the telescope. Also the direct registration on a magnitude scale has proved to be an advantage. Such items as time and height of maxima and minima and epochs of ascending branches can directly be read off the registrations, thereby avoiding lengthy reductions as is required for the many readings with a direct photometer.

An important disadvantage of the instrument is the restriction of its use to rapidly changing variable stars. Even when the adjustment of the optics to a certain distance and position angle of the two stars, and the checking up whether the sky diaphragms do not contain disturbing stars can be done quickly, there will be no important saving of time as compared to the measurement

with a direct photometer, in the case of studying several long period variables in one night. This disadvantage, however, can be made less serious, if, as has been done with success in the latest photometer, the amplifier can be switched over to d.-c. performance. Then, by covering all but one of the diaphragms, stopping the motion of the light switch, and connecting the pre-amplifier to a meter of recorder, the photometer can be used for d.-c. measurements.

A detailed description of the photometer, with schemes and diagrams, shall be published in the near future in the B.A.N.

LIMITS OF SENSITIVITY AND PRECISION ATTAINABLE BY PHOTOELECTRIC METHODS: CRITICAL SUMMARY AND COMPARISON OF VARIOUS TECHNIQUES

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THE ASTROPHYSICAL INFORMATION that can be derived by the analysis of a beam of light from a distant source is, in the last analysis, subject to the fundamental limitation set by the number of quanta arriving in the observation time. The ideal detector or light sensitive device at the focus of the telescope would be able to record the arrival of each quantum, and the indication would simply be the total number received in a specified range of the spectrum. Then the accuracy attainable in a given time could be easily calculated from the well-known statistical principle that for randomly spaced events.

$$\overline{(nt - n_0t)^2} = n_0t \qquad (nt \gg 1) \tag{1}$$

where n_0 = average rate of arrival of quanta in the specified spectral range

nt = number arriving in a particular time interval t.

Expressed as the conventional ratio of signal S to noise N this is equivalent to

$$S/N = (n_0t)^{1/2} \tag{2}$$

Even with the hypothetical ideal detector, disturbing influences arising mainly from the earth's atmosphere would prevent

reaching this calculated limit. Among these influences are background radiation from the light of the night sky, scintillation caused by atmospheric turbulence, and slower fluctuations caused by variations in atmospheric transparency. A discussion of methods of minimizing these disturbances may be postponed, however, until after a consideration of the properties of actual, rather than ideal, detectors of radiation.[1]

Quantum Efficiency

In the broad sense, the basic phenomenon in the photographic plate is similar to that in the photoelectric cell. A particular quantum acts on an electron to produce a recordable event. The best photoelectric cathodes are, however, considerably more efficient than the photographic plate. The quantum yield of a typical antimony-cesium surface at 4000 A is 12 per cent, i.e., about one out of every eight incident quanta produces a photoelectron. Exceptional cases of efficiency as high as 25 per cent have been recorded. The photographic plate requires about 100 quanta to produce a developable plate grain in the same region of the spectrum.[2] In the red and near infrared portions of the spectrum, the best photoelectric cathode, the cesium-oxide-on-silver, has a typical efficiency of only about 0.3 per cent, or 40 times poorer than the antimony-cesium surface in the blue. But the sensitivity of the photographic plate in this region is also poorer than it is in the blue,[3] and the photosensitive cathode may therefore be said to be superior in quantum efficiency over the whole range from 3000 A to 10,000 A.

Recording the release of a photoelectron is not as simple as developing an exposed plate grain, but, as will be shown later, the technique is in a fairly satisfactory state; there can be nearly 100 per cent recovery of the fundamental information contained in the number of photoelectrons produced. For photoelectric observations, then, the observational accuracy can approach the theoretical limit given by the following modification of equation (2):

$$S/N = (\epsilon n_0 t)^{1/2} \qquad (3)$$

where ϵ is the quantum efficiency. Improvements in ϵ will affect the signal-to-noise ratio not in direct proportion, but as $\epsilon^{1/2}$. In the region covered by the antimony-cesium surface there is room for an improvement by a factor of only 2 or 3; in the red and near infrared a factor of 10 to 15 is theoretically possible if 100 per cent quantum efficiency can be achieved.

The superior quantum efficiency of photoelectric cathodes means that the photoelectric method should yield the desired information about any single object in a shorter time than any other method. It also means that in attempting to measure faint objects, the photoelectric method will be limited by low contrast against the background light of the night sky, just as sky fog sets the limit in photographic exposures. Since many questions of observing technique are influenced by this limitation, a quantitative evaluation of sky background light is necessary.

Sky Background

Van Rhijn[4] found that the visual brightness of the sky at the Mount Wilson pole was magnitude 21.0 per square second. A reasonable correction for starlight at galactic latitude 28° and for scattered light from the Milky Way gives a revised figure 21.5 per square second for points far from the galactic plane. Strömgren[5] adopts as a minimum magnitude 21.8 per square second. The background light may of course be much brighter than the minimum if the observed area is in the Milky Way, or near the ecliptic (zodiacal light), or near the horizon (permanent auroral glow).

From the information that a standard candle at a kilometer equals visual magnitude +0.8, one may derive the useful relation

$$\log L = 2 \log D - 0.4\, m_v - 8.97 \qquad (4)$$

where L = luminous flux in visual lumens
D = diameter of telescope in inches
m_v = visual magnitude of star.

If we adopt a visual sky brightness of 21.5 mag. per square second, it follows that a focal plane diaphragm d inches in diameter at the focus of a telescope of focal length f inches will furnish an amount of light L_s from the sky

$$\log L_s = 2 \log d - 2 \log F - 7.05 \tag{5}$$

where $F = f/d =$ the focal ratio of the telescope.

These relations are sufficiently accurate if the filter used roughly matches the sensitivity curve of the eye. Since the sky may be assumed to have a temperature somewhat higher[6] than the 2870°K. source normally used in testing cathode response, the high blue sensitivity of the antimony-cesium surface will mean a sky current about twice as large as that predicted using equation (5) with the manufacturer's rating of the cathode in amperes per lumen from a source at 2870°K. Cesium oxide surfaces whose infrared response extends out to 10,400 A will give a large sky current from the intense OH emission bands[7] in the light of the night sky.

If the optical and mechanical properties of the telescope are of a high standard, the diaphragm size may be reduced to that just adequate to admit the entire image of the star. The apparent angular diameter will of course depend on seeing conditions. Because the image always has an outer fringe of low intensity which contains an appreciable fraction of the light, the diaphragm must be larger than the photographic image diameter. A margin of safety must be allowed so that slight wandering or small blowups in the seeing do not cause loss of light. Diaphragms as small as 5 seconds of arc are possible in good seeing, but 10 seconds has been a more usual working minimum. The 78 square seconds contained in a 10-second diaphragm admit sky light equivalent to a star of visual magnitude 16.8, under the conditions assumed in equation (5). For stars fainter than this, skylight will be dominant in setting the noise level, independent of the aperture of the telescope. Larger telescopes do improve the signal-to-noise ratio, however, because of the greater total number of photoelectrons per unit time. The improvement goes as the square

root of the area of the objective, or in direct proportion to the diameter.

In order to operate reliably under seeing-limited conditions, it is necessary to have the same type of off-axis auxiliary guiding eyepiece used in long photographic exposures, in order to have a continuous check on the centering of the desired object. Since the faintest objects are below the limit of vision, the guiding eyepiece must have graduated cross-slides to facilitate accurate offsets from stars easily seen in the on-axis diaphragm.

For smaller telescopes, where centering and guiding to an angular precision of the order of one second of arc is not feasible, the smallest diaphragm is usually of the order of 1 millimeter in diameter. Here the sky light, as given by equation (5), depends only on the F ratio of the telescope, and the signal-to-noise ratio improves in proportion to the area of the objective. If there are chromatic errors, as for the violet image from a visual refractor, a larger diaphragm must be used, and sky noise will be more serious. Faint nebulous objects of considerable angular diameter likewise suffer an increased noise level from the sky background. Of course moonlight, or sky illumination from nearby cities, will also raise the level of sky noise.

It has been assumed in the foregoing that the cathode dark emission is negligible compared with the photoemission. Refrigeration is always necessary to bring the dark current down to such a level when operating under seeing-limited conditions. Dry ice is the usual refrigerant, since it suffices to reduce the dark emission below the sky current level; still lower temperatures would offer no advantage. When working with brighter stars the dark current from cesium-antimony surfaces may be smaller at room temperature than the photocurrent from star plus sky, and then refrigeration is an unnecessary complication.

Electronic Techniques for Registering the Photocurrent

In the earlier part of the historical development of photoelectric methods, the fundamental limitations discussed thus far

were not the controlling factor because the instruments for registering the photocurrent had limitations of their own which put in noise often far in excess of that set by the statistics of the electrons. The situation has vastly improved in the last decade, and it is now usually the case that the indicating equipment does not add any appreciable noise to degrade the original information contained in the photoelectrons themselves.

The techniques of measurement may be divided into two general methods: (1) charge integration, and (2) current measurement.

Charge integration is theoretically limited in accuracy only by the statistics of counting the randomly spaced electrons. Current-measuring methods, on the other hand, have a limit set by the shot-noise equation

$$\overline{i_s^2} = 2eI\Delta f$$

where i_s is the deviation from the average current I, e is the electronic charge, and Δf is the bandwidth of the recording device. For the d.-c. amplifier often used in registering photocurrents, where the high-frequency response is limited by a resistance-capacity combination giving a time constant $\tau = RC$, it may be shown that the equivalent bandwidth for noise is $\Delta f = 1/4RC$. If we assume an exposure time $t = 1/\Delta f = 4RC$, the signal-to-noise ratio is

$$S/N = I/(2eI\Delta f)^{1/2} = (It/2e)^{1/2} \tag{6}$$

When this is compared with the charge integration method

$$S/N = (\epsilon n_0 t)^{1/2} = (It/e)^{1/2} \tag{7}$$

it is seen that the current measurement method is poorer by a factor of $2^{1/2}$. The reason for the difference is that not all parts of the exposure interval are given equal weight in registering the final deflection. The circuit's memory for the rate of charge collection is poorer for the early part of the exposure interval than it is for the last part. As a practical matter, however, the current measurement method has the partially compensating advantage that it gives a definite pointer reading for each intensity, rather than a rate of charge accumulation. Variable sky

transparency, poor guiding, and malfunctioning of the amplifier are more quickly detected in the variation of a steady reading than in the variation of a rate.

The earliest indicating devices in the history of photoelectric photometry were of the charge integration type, since only electrometers provided anything like the required sensitivity. In most cases, the need to swing the instrument around on the end of a telescope prevented reaching high enough sensitivity to show fluctuations set by the statistics of the photoelectrons. Sinclair Smith[8] did reach the statistical limit with a Hoffman electrometer at the coudé focus of the 60-inch telescope, where a very stable mounting could be provided. The modern vibrating condenser electrometer[9] should give nearly equal performance in a more rugged and portable form. One limitation of this method of measurement is, however, the rather limited range of intensity that can be covered by the rate-of-charge method. A series of neutral absorbing glasses can be used to equalize intensity somewhat. Lack of complete neutrality would disturb color systems; of course any absorber throws away part of the received quanta. An alternative would be a series of low-leakage condensers which could be switched in to change the capacity of the system.

Pulse counting is another method of charge integration that is very well adapted to use on the end of a telescope. The historical and practical applications of this method to astronomical photometry are treated in another paper in the symposium.[10] It was the advent of the secondary image photomultiplier that made counting methods fairly simple and straightforward, since the output pulses consist of about one million electrons each. The rather complicated scaling circuits needed to handle high counting rates have now become standardized because of their wide use in nuclear physics. When the ultimate limit set by the statistics of the photoelectrons can be attained so directly, it might seem that counting methods are the obvious first choice. There are, however, one or two drawbacks to be considered.

The range of intensities which may be covered with linear response is not as great in the counter method as it is in straight current measurement, because of dead time in the scaler flip-flop

circuits. Redman and Yates[11] have discussed this point and showed how the effect may be reduced by a specially designed first-stage with a dead time less than one microsecond, a reduction of a factor of five over the more ordinary circuit. Even so a counting loss of 1 per cent is to be expected for a current of 10,000 electrons per second, or 1.6×10^{-15} ampere at the cathode. This is not a large current under usual operating conditions. The bright stars that are ordinarily used for comparison stars and standards are very likely to come in the range of nonlinearity, and thus fall outside the region where the most obvious benefit of the photoelectric method, that of complete linearity, applies. And while it might seem that a photoelectron is either counted or not counted, there is enough variation in the size of the output pulses so that the choice of the clipping level does affect the output. Stable voltages are therefore required, just as in a current amplifier. Engstrom's suggestion[12] of improving the signal to noise ratio by attempting to set the clipping level to distinguish between thermionic electrons and photoelectrons is not practical in actual operation, because, as shown in the previous section, the light of the sky insures that the photocurrent will always exceed the dark emission from a refrigerated cathode.

While the pulse-counting method is somewhat less flexible, and requires more complicated apparatus, it is probably the one best suited to reaching the ultimate accuracy on stars which may barely be detected by long photographic exposures.

Techniques of Current Measurement

If one chooses to record the output of the photoelectric cathode by a current-measuring device, obviously an amplifier of considerable gain will be necessary. Before the advent of the multiplier phototube, d.-c. amplifiers were almost universally used. In the simplest form, where the grid of the so-called electrometer tube was used to measure the voltage drop across a load resistor in series with the photoelectric cell, it was usually the

amplifier rather than the shot effect in the photocurrent which determined the noise level. The combined noise voltage from the two sources is given by the equation

$$\begin{aligned} \overline{e_n^2} &= \overline{e_t^2} + \overline{e_s^2} \\ &= 4kTR\Delta f + 2eIR^2\Delta f \end{aligned} \tag{8}$$

where e_s is the fluctuation noise voltage due to shot effect, e_t is the fluctuation voltage due to thermal noise in the resistor, k is the Boltzmann constant, and T is the absolute temperature. At 300°K. this reduces to

$$\overline{e_n^2} = 1.64 \times 10^{-20} R\,(1 + 20IR)\Delta f \tag{9}$$

It is obvious that the IR drop in the load resistor must be at least 0.05 volt for the shot effect to equal or exceed thermal noise. Unless this threshold is reached, the amplifier noise of course dominates. At the intensity levels and photocurrents met with in astronomical photometry, this condition cannot be fulfilled without impossibly high values of the load resistor. A further source of noise to be considered is the shot effect of the grid current of the electrometer tube itself. If the tube be operated at a plate voltage of only 4 volts and a plate current of only 10 microamperes, the grid current may be as low as 5×10^{-16} ampere, but even this value may override the contribution from the shot effect of the cathode emission itself.

In fact, shot-limited amplification of small photocurrents by means of the traditional load resistor appears to be impossible with practical values of the resistor, unless there is some preliminary multiplication. H. L. Johnson[13] showed that gaseous multiplication of the order of 50 in a simple photoelectric cell is just adequate to achieve shot-noise limiting. When allowance is made for the inevitable contribution of sky light to the noise, however, a smaller (and inherently more stable) value of the gaseous multiplication suffices. For example, a 1-millimeter diaphragm at the focus of an F/5 telescope admits, according to equation (5), a quantity of sky light

$$L_s = 5 \times 10^{-12} \text{ lumen}$$

With a cathode yield of 20 microamperes per lumen, a conservative value for cesium oxide surfaces, the cathode emission I_c will be

$$I_c = 10^{-16} \text{ ampere}$$

Then the condition for the threshold of shot-limited operation is

$$20\,(\,|\,\mu I_c\,| + |\,I_g\,|\,)\,R > 1 \qquad (10)$$

where μ is the gaseous amplification, assumed not to add appreciably to the randomness of the cathode emission. If we take $\mu = 15$, a safe and attainable value, numerical substitution gives

$$R > 3 \times 10^{13} \text{ ohms}$$

which is a practical and usable value of the load resistor.

With a load resistor as high as 5×10^{13} ohms, however, the time constant of the input circuit becomes prohibitively long. An input capacity of 10 micromicrofarads is typical; the time constant would then be 500 seconds, and a single deflection could be obtained only every half hour. Kron[14] has described two methods of reducing the effective time constant to 1 or 2 seconds and still

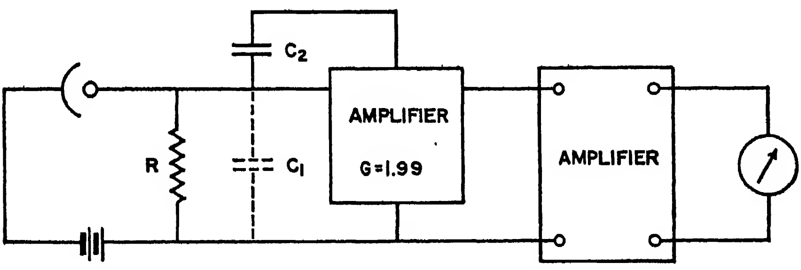

FIGURE 1. Reduction of input time constant by positive feedback. In the example shown $C_1 = C_2$.

maintaining the high load resistance. The first method shown in Figure 1 uses positive feedback, and reductions in the time constant by a factor of at least 100 are feasible. High gain stability is required because the circuit is close to the threshold of feedback oscillation. In Figure 2, the second method, suggested by H. L. Johnson,[15] is shown. It uses negative feedback and has the advantage of being insensitive to gain stability. The effective

time constant is reduced by a factor approximately equal to the loop gain of the feedback amplifier. Distributed capacity across the high load resistor cannot be compensated, however. The greatest practical difficulty with the circuit has been the unpredictable transient response of the high load resistors so far obtainable. Some show overshoot and others excessive lag. The steady state value of the response obeys Ohm's law satisfactorily, but the relaxation time of the transient phase may be considerably longer than the calculated effective time constant. Some improvement can be realized by a compensating transient network in the feedback line.

With the advent of the multistage secondary emission multi-

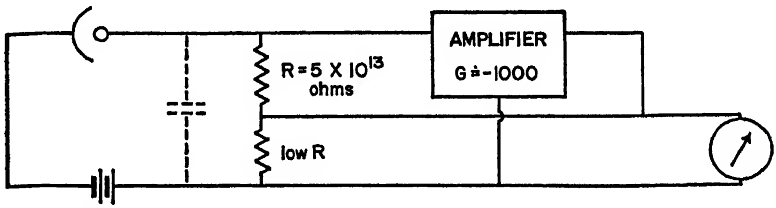

FIGURE 2. Reduction of input time constant by negative feedback.

plier, difficulties with thermal noise in the load resistor practically disappeared, and a very close approach to shot-limited operation is straightforward. As shown by Zworykin, Morton and Malter,[10] the multiplication process increases the noise relative to the signal by a small factor of the order of $m/(m-1)^{1/2}$, where m is the multiplication per stage. Since m is usually as large as 4, the signal-to-noise ratio deteriorates by only about 15 per cent. The million-fold greater "grain-size" of the electric charge in the output greatly relaxes the requirements in designing further amplification. Equation (10) shows that shot noise will dominate if the IR drop in the input resistor is greater than 0.05 microvolt. Linnell discusses some successful designs in another paper in this symposium. Zero stability and gain stability are far more important than inherent noise.

A.-C. Versus D.-C. Methods

Both a.-c. and d.-c. methods can, with proper design, give stable, linear, and drift-free amplification. The former prejudice in favor of a.-c. methods, particularly among engineers, was based on the feeling that the "tag" put on the light beam by the chopper enabled one to cancel off drift and dark current. The drift problem is now negligible, and the dark current should, in any case, be reduced by refrigeration to a value less than the photocurrent, or it will raise the noise level. A simple chopper rejects half of the received quanta at the outset, and considerable care is needed in the output rectifier to preserve linear response for small signals.[17]

The attractiveness of the null principle has led to various devices where the photoelectric detector is used only as an indicator of the equality of two beams of light, one of which is perhaps from an artificial source. This approach fails to utilize the outstanding advantage of the photoelectric method—its linear response; in addition, it makes necessary continual attention to and frequent checking of a calibration curve. If there is an appreciable noise level, impersonal accuracy requires a continuously recording servomechanism to maintain the null balance. In certain instances the null method may offer compensating advantages, such as logarithmic response. Walraven's[18] differential photometer is a case of this sort; the carefully made wedge provides a strictly linear relation between magnitude and displacement.

Alternating-current methods do have a field of great usefulness in differential photometry. Often the desired information is a small difference between two larger light intensities. Examples are the difference between sky and sky plus star, between two color filters on the same star, between two components of partially polarized light, or between a weak absorption line and the continuum. For all such applications the linear response of the photoelectric method is a great advantage, because it makes

possible direct subtraction of two quantities of light. Preserving the advantage is an added reason for careful attention to linear response throughout the associated amplifiers and indicators.

With d.-c. amplifiers, differential methods have regularly been used with a "back-and-forth" exposure schedule, dark being largely ignored. Alternation is rarely more rapid than 10 seconds in each position. This time may be shortened to a small fraction of a second by a.-c. amplification. If the frequency spectrum of the atmosphere-generated noise (either scintillation or transparency variations) shows a falling trend as the frequency increases, there may be quite an appreciable improvement in going to a.-c. methods. J. S. Hall's report[19] in this symposium reviews the technique, with a full consideration of atmospheric effects.

Dual-channel photometry involving two multipliers or photoelectric cells with completely separate amplifiers has not been much employed because of doubt about maintaining constancy of cathode response and of amplifier gain. Where the two beams involve different components of the light of the same star, as in polarization studies, this objection partly disappears. Hiltner's[20] phenomenally high accuracy obtained in a dual-channel photometer utilized this advantage. There was the added help that a continual check on balance was available through the insertion of a depolarizer. In other applications, a low-intensity radioactive light source could be used as an intensity monitor for the separate cathodes.

Image Tubes

The greatest difference between the photoelectric cell and the photographic plate as a collector of astronomical information is, of course, the fact that the photoelectric cell gives information on only one selected element of the scene being viewed and is therefore enormously inferior to the photographic plate in that it cannot collect simultaneous information about all of the picture elements in one contiguous part of the sky. There is a compensating advantage in the fact that in the one selected element

of arbitrary size, the photoelectric cathode, in combination with a Fabry field lens, integrates all the light received. This makes it a very useful device in the comparison of point sources such as stars and luminous areas such as gaseous nebulae and external galaxies.

There have been many proposals that some form of the image tube used in television could be adapted to the end of a telescope as a substitute for the photographic plate. The higher quantum efficiency could be used to gather in a shorter time the information now requiring long photographic exposures. Such a development is, in principle, quite possible, and may be not many years in coming. It may be doubted, however, that the linearity of the photoelectric process can be preserved through all the processes needed to record in numerical form all the separate bits of information on an astronomical photograph. And since the present limitation on recording faint stars with existing large telescopes is the contrast between the seeing disk of the star and the light of the sky, image-tube techniques will have to provide a higher contrast sensitivity than the photographic plate to bring out anything below the present limit of detection. The latitude for improvement in this direction may not be very great, but the gain in speed is a real possibility. The more immediate problem is to develop a technique of registering with an image tube a surface brightness as low as that of the night sky.

Summary and Conclusions

1. *Advantages of the photoelectric cell as a detector.* The photoelectric cathode is the detector which, because of its relatively high quantum efficiency, comes closest to the ideal of registering the arrival of every quantum. Its linear response is an enormous practical advantage in accurate photometry. At present only one small area may be handled at once at astronomical intensity levels; improvements in image tube techniques may in some degree overcome this limitation.

2. *Instrumental limitations.* Instrumental development has

reached the stage where essentially all the information contained in the released photoelectrons can be preserved in the output of the amplifier or other recording equipment. The various techniques show relatively minor differences in their ability to approach this ideal, with counting methods giving a slight superiority for very faint objects.

3. *Limitations on accuracy.* The earth's atmosphere is the controlling factor for both bright and faint objects. At the faint end the light of the night sky greatly exceeds the light of the star and determines the noise level. Reduction of noise by using the smallest possible diaphragm is limited by the quality of the seeing. For brighter objects, where there is an ample number of photoelectrons for good statistical accuracy, the effective noise level is set by scintillation or by small variations in the atmospheric transparency. The latter class of errors may be minimized by differential or a.-c. techniques.

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